GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

# PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. G-41-663(Continuation of G-41-636) GTRI/~~GIT~~ DATE 3 / 22 / 84

Project Director: J.L. Wood School/~~Lab~~ Physics

Sponsor: Department of Energy, Oak Ridge Operations

Type Agreement: Contract No. DE-AS05-80ER10599, Mod. A005

Award Period: From 2/1/84 To 1/31/85 (Performance) ---- (Reports)

Sponsor Amount:

| | This Change | Total to Date |
|---|---|---|
| Estimated: | $ 80,000 | $ 80,000 |
| Funded: | $ 80,000 | $ 80,000 |

Cost Sharing Amount: $ 8,735 Cost Sharing No: G-41-341

Title: Nuclear Structure From Radioactive Decay

## ADMINISTRATIVE DATA

OCA Contact William F. Brown ext. 4820

1) Sponsor Technical Contact:

Mr. S. Whetstone, ER-23GTN
U.S. Department of Energy
Washington, D.C. 20545
Division of Nuclear Physics
Ofc of High Energy + Nuclear Physics

2) Sponsor Admin/Contractual Matters:

Ms. Joyce Carringer
Procurement and Contracts Division
Department of Energy
Oak Ridge Operations
P.O. Box E
Oak Ridge, TN 37830 (615) 576-7564

Defense Priority Rating: None

Military Security Classification: None

(or) Company/Industrial Proprietary: None

## RESTRICTIONS

See Attached Gov't Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed or anticipated

## COMMENTS:

Mod. A005 adds $80,000 partial funding through 1/31/85. Revised total contract value (including prior project numbers) is $355,000.



## COPIES TO:

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

## SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 6-15-87

Project No. G-41-663 School/~~Lab~~ Physics

Includes Subproject No.(s) N/A

Project Director(s) J.L. Wood GTRC / ~~GIT~~

Sponsor Department of Energy, Oak Ridge Operations

Title Nuclear Structure From Radioactive Decay

Effective Completion Date: 1/31/87 (Performance) 1/31/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [x] Closing Documents
- [x] Final Report of Inventions - Questionnaire sent to P.I.
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. G-41-636 Continued by Project No.

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COVER SHEET

FOR TRIP REPORTS SUBMITTED TO THE

OFFICE OF ENERGY RESEARCH

Destination(s) and Dates for
Which Trip Report Being Submitted: FINLAND / WEST GERMANY / BELGIUM
10/23/86 – 01/06/87

Name of Traveler: JOHN L. WOOD

Joint Trip Report [ ] Yes

[X] No

If so, Name of Other Traveler(s): ____________________

____________________

FOREIGN TRAVEL REPORT

Name of Traveller: John L. Wood

Position: Associate Professor of Physics

DOE Organization Represented: Office of High Energy and Nuclear Physics, Division of Nuclear Physics

Organization: Georgia Institute of Technology

Contract Number: DE-AS05-80ER10599

Date of Report: February 1987

Date of Trip: October 23, 1986 - January 6, 1987

Places Visited: Finland (University of Jyväskylä, Jyväskylä); West Germany (GSI, Darmstadt; University of Mainz, Mainz); Belgium (IKS Leuven; IKF Gent).

Purpose of Trip: To conduct experiments at the Jyväskylä cyclotron and discuss $0^+$ excited states in nuclei. To discuss physics accessible with 100 MeV/u heavy ions and nuclei far from stability in Darmstadt. To discuss and lecture on shape coexistence in Mainz and work on manuscript preparation relating to earlier laser measurements of gold isotope and isomer shifts. To continue collaborations in Leuven and Gent on nuclear orientation, nuclei far from stability and shape coexistence.


ABSTRACT

The experimental work in Jyväskylä concentrated on in-beam $\gamma$-ray and conversion-electron studies of low-medium spin states in $^{118,120}Te$ populated in the $(\alpha,n)$ reaction. The goal of these measurements is to ascertain whether or not shape coexistence occurs at low energy. Lectures and discussions were held on excited $0^+$ states, electric monopole transitions and shape coexistence

in nuclei. The work in Darmstadt focused on studies of nuclei far from stability, both current studies in the neutron-deficient rare-earth region and projected study of neutron-rich nuclei with 100 MeV/u heavy ions. The latter will become available at GSI Darmstadt with the new "SIS 18" booster/storage ring-cooler presently under construction. In Mainz, results from the laser spectroscopy measurements on gold isotopes were prepared for publication and discussions on shape coexistence were pursued. In Leuven, low-temperature nuclear orientation of neutron-deficient isotopes of polonium, astatine, radon, and francium were discussed and preliminary results scrutinized. The study of $\alpha$ decay as a spectroscopic tool was discussed and results of $\alpha$ decay of oriented nuclei considered for clues to information on nuclear shape changes. In Gent, nuclear shape coexistence was discussed, new topics on coexistence were opened up and manuscripts on shape coexistence were prepared for publication.

Cost of Travel: $1,301 (Transatlantic airfare; airfare Jyväskylä - Frankfurt; train fare Darmstadt - Leuven; some local expenses). All other expenses covered by host institutions or the author.

DETAILED TRIP REPORT

This trip involved collaborations, new initiatives and discussions on shape coexistence in nuclei and the study of nuclei far from stability. These are the two major themes of research on this contract.

Experiments were conducted in Jyväskylä on the excited states of $^{118,120}$Te. The reactions chosen were $^{115}$Sn($\alpha$,n)$^{118}$Te and $^{117}$Sn($\alpha$,n)$^{120}$Te. These reactions, if conducted just at or below the Coulomb barrier (12 MeV) give a good population of low-spin states. Gamma-ray and conversion-electron spectroscopy were taken in beam. The goal of these measurements is to show that shape coexistence is possible in the even-mass Te isotopes. Shape coexistence is characterized by electric momopole transitions between low-spin states.

Lectures and discussions on shape coexistence in nuclei were also pursued in Jyväskylä. Theoretical ideas developed by the author and colleagues in Gent (see below) suggest widespread occurrence of shape coexistence in nuclei, albeit not always easy to see. Plans for experiments at the new Jyväskylä cyclotron (for which construction will soon begin) were discussed, especially pertaining to shape coexistence. Groundwork was laid for a major review of excited $0^+$ states and electric monopole transitions in nuclei.

In Darmstadt, discussions of nuclei very far from stability were pursued. Specifically, new data in the proton-rich N = 82 region, obtained at the GSI, Darmstadt on-line isotope separator (ISOL), the ISOLDE ISOL at CERN, Geneva and the ISOCELE ISOL at Orsay, France, were discussed. These data reveal that the major closed shell at N = 82 remains intact very far from stability.

Special focus in Darmstadt was given to forthcoming instrumentation and plans for the SIS-18 heavy-ion synchrotron and ESR storage-cooler ring, presently under construction at GSI (see the attached copy of the GSI Nachrichten for 11/86). Of special interest to the author was plans for a separator for projectile fragments. This will provide exotic nuclei far from stability and secondary (radioactive) beams of exotic nuclei. Isotopes even further from stability than the very recent discoveries at GANIL in Caen, France will be accessible with this device. For the first time, it is expected that detailed mapping of the proton <u>and</u> neutron drip lines will be possible up to medium-heavy nuclei. Secondary beams will permit reactions leading to highly exotic (and unstable) nuclei and such measurements as inverse Coulomb excitation.

In Mainz, results from the laser spectroscopy measurements on gold isotopes, made in December 1985 at the ISOLDE ISOL, were prepared for publication (title page and abstract attached). Discussions of shape coexistence were pursued and plans for future experiments made. (The Mainz laser group are the World leaders in optical hyperfine spectroscopy on-line with unstable isotopes. These are five faculty and 15-20 graduate students in the program.)

In Leuven, low-temperature nuclear orientation of neutron-deficient isotopes of polonium, astatine, radon, and francium were discussed. These nuclei decay by $\alpha$-particle emission. Very large anisotropies are observed, suggesting an extraordinary sensitivity of direction of alpha-particle emission to the nuclear shape. The possibility of extracting information on small shape changes between parent and daughter nuclei from the data was discussed. These data are a completely new view of nuclear structure.

The author was informed that plans had been approved for a small high-current cyclotron to be coupled to the CYCLONE cyclotron at Louvain-la-Neuve (the facility used by the Leuven group, located 20 miles away). This will provide intense secondary beams, accelerated by CYCLONE, for astrophysical and other studies.

In Gent, the collaboration on nuclear shape coexistence was pursued (a NATO travel grant has just been accorded to the author and Prof. K. Heyde in support of this collaboration.) A large paper on theoretical treatment of shape coexistence was edited for publication in Nuclear Physics A (galley title page attached). A major review of shape coexistence in even-mass nuclei was planned. Unsolved problems to be attacked in the next year were discussed -- of primary interest is the lack of mixing between states of different shape -- this mixing is only ~7% of current theoretical predictions, and is not understood.

APPENDIX

Full Itinerary: Oct. 23-24 en route Atlanta-Jyväskylä

Oct. 24 - Nov. 27 Jyväskylä, Finland
Nov. 27 - Dec. 15 Darmstadt, West Germany
Dec. 15 - Jan. 6 Leuven, Belgium with visits to Gent
Jan. 6 en route Leuven-Atlanta

| Persons Contacted (title) | Subject of Discussion |
|---|---|
| **Jyväskylä** | |
| J. Kantele (Professor) | $0^+$ states, E0 transitions, the new cyclotron project. |
| P. Lipas (Professor) | interacting boson model. |
| A. Passoja (Senior Research Scientist) | $0^+$ states, E0 transitions. |
| R. Julin (Senior Research Scientist) | $0^+$ states, E0 transitions. |
| J. Kumpulainen (Student) | $^{118,120}Te$ measurements. |
| J. Äystö (Senior Research Scientist) | the IGISOL (ion-guide isotope separation on-line) project. |
| **Darmstadt** | |
| E. Roeckl (Senior Research Scientist) | nuclei far from stability, the GSI ISOL project, SIS-18 plans. |
| O. Klepper (Senior Research Scientist) | GSI ISOL decay scheme studies. |
| D. Schardt (Research Sci.) | proton rich nuclei near N = 82 |
| T. Kühl (Research Scientist) | the GSI ISOL on-line laser experiments on In, Cd, Sn. |
| **Mainz** | |
| E. Otten (Professor) | on-line laser spectroscopy of exotic isotopes. |
| R. Neugart (Assoc. Prof.) | laser spectroscopy. |
| P. Egelhof (Research Sci.) | results of the Au laser experiments. |

| | |
|---|---|
| K. Wallmeroth (Student) | results of the Au laser experiments. |

Leuven

| | |
|---|---|
| R. Coussement (Professor) | students, manpower needs. |
| L. Vanneste (Professor) | low-temperature nuclear orientation. |
| M. Huyse (Senior Research Scientist) | LIGISOL (Leuven ion-guide isotope separation on-line) project. |
| J. Wouters (Student) | alpha-decay of oriented nuclei. |
| E. Van Walle (Research Sci.) | plans for him to join UNISOR (Oak Ridge) project. |

Gent

| | |
|---|---|
| K. Heyde (Professor) | shape coexistence in nuclei. |

General Remarks

New facilities are planned or under construction in Jyväskylä (a "medium-K" cyclotron), Darmstadt-GSI (SIS-18/ESR: a heavy-ion synchrotron with storage ring and cooler), and Louvain-la-Neuve (a high-current small cyclotron for production of secondary beams to be accelerated by the existing CYCLONE facility). In Jyväskylä the physics focus will be on high-quality low-energy nuclear structure. In GSI the physics will be exotic heavy-ion physics at energies of 100 MeV/u. In Louvain-la-Neuve astrophysical studies are planned. There are no plans in the USA for any of these types of facility. When one considers also e.g., ISOLDE III at CERN, Geneva -- a multi-beam multi-device ISOL facility for detailed study of nuclei far from stability, NIKHEF-K in Amsterdam -- a high resolution electron accelerator, and GANIL in Caen (France) -- a 40-60 MeV/u heavy-ion accelerator: It is evident that the USA has not only lost nearly all its initiatives in low-energy nuclear physics, but is going to stay out of the forefront for the forseeable future. In the opinion of this author, the USA nuclear physics community needs some initiatives for its future research in low-energy nuclear physics.

Literature Acquired

1. JYFL (Jyväskylä) Annual Report 1986.

2. EPM (Extended Phonon Model) Calculations of E2/M1 Mixing Ratios for Even Samarium Isotopes $^{146,152}$Sm, J. Suhonen, JYFL preprint 23/86.

3. Helium-Jet Techniques in On-Line Isotope Separation, J. Ärje, JYFL preprint 20/86.

4. Selected Aspects in the Structure of Beta-Delayed Particle Spectra, J. Honkanen, J. Aysto and K. Eskola, JYFL preprint 14/86.

5. Separation of Fission Products by the Ion Guide Fed Isotope Separator, IGISOL, J. Aysto et al., JYFL preprint 17/86.

6. Electronic Factors for K-Shell-Electron Conversion Probability and Electron-Positron Pair Formation Probability in Electric Monopole Transitions, A. Passoja and T. Salonen, JYFL preprint 2/86.

7. Electromagnetic Decay of $0_2^+$ and $0_3^+$ States in the N=88-90 Nuclei of $^{150,152}$Sm, A. Passoja et al., Journal of Physics G12, 1047-1057 (1986).

8. E0 Transitions in $^{202,204}$Pb and Intruder State Systematics of Even-Even Lead Isotopes, J. Kantele et al., Physics Letters 171B, 151-154 (1986).

9. Particle-Hole Multiplets in $^{146}$Gd from In-Beam Studies of Non-Yrast Levels, S. W. Yates et al., Zeitschrift für Physik A324, 417-432 (1986).

10. Electromagnetic Properties of Low-Spin States in $^{102,104}$Pd, M. Luontama et al., Zeitschrift für Physik A324, 317-324 (1986).

11. The Beta Decay of $^{48}$Mn: Gamow -Teller Quenching in fp-Shell Nuclei, T. Sekine et al., GSI preprint 86-54.

12. A Review of Experimental Evidence for Octupole Deformation, J. Zylicz, GSI preprint 86-29.

13. Spins, Moments and Charge Radii of $^{104-107}$In Determined by Laser Spectroscopy, J. Eberz et al., GSI preprint 86-22.

14. Optical Spectroscopy Using Mass-Separated Beams: Nuclear Properties of Unstable Indium and Tin Isotopes, T. Kühl et al., preprint.

15. Experiments for the Investigation of Proton Radioactivity, S. Hofmann et al., preprint.

16. Heavy Elements - Experiments on Synthesis and Decay, S. Hofmann et al., preprint.

17. Evidence for $^{264}108$, the Heaviest Known Even-Even Isotope, G. Münzenberg et al., Zeitschrift für Physik A324, 489-490 (1986).

18. Identification of a 3.2 μs Isomer in $^{76}Rb$, S. Hofmann et al., Zeitschrift für Physik A325, 37-43 (1986).

19. Beta-Decay of $^{151}Yb$, P. Kleinheinz et al., Zeitschrift für Physik A323, 705-706 (1985).

20. Decay Studies of Neutron-Rich Radium and Actinium Isotopes, Including the New Nuclides $^{232}Ra$ and $^{232,234}Ac$, K.-L. Gippert et al., Nuclear Physics A453, 1-14 (1986).

21. Isotope Shift of $^{182}Hg$ and an Update of Nuclear Moments and Charge Radii in the Isotope Range $^{181}Hg$ - $^{206}Hg$, G. Ulm et al., Zeitschrift für Physik A325, 247-259 (1986).

22. Sudden Change of the Nuclear Charge Distribution of Very Neutron-Deficient Gold Isotopes Detected by On-Line Resonance Ionization Mass Spectrometry, K. Wallmeroth, doctoral dissertation, 1986, Universität Mainz.

23. The F-Spin Symmetric Limits of the Neutron-Proton Interacting Boson Model, P. Van Isacker et al., Annals of Physics 171, 253-296 (1986).

24. The Interacting Boson-Fermion Model: Bose-Fermi Symmetries and Supersymmetries, J. Jolie, doctoral dissertation, 1986, Rijksuniversiteit Gent.

25. On the Nature of Low-Lying $7/2^+$ States in Odd-A Tc, Rh and Ag Nuclei, K. Heyde and V. Paar, Physics Letters 179B, 1-3 (1986).

26. Rearrangement Effects in Shell-Model Calculations Using Density-Density Interactions, M. Waroquier et al., to be published in Physics Reports.

27. Direct Spin Determination of On-Line Separated Isotopes by Nuclear Orientation and Nuclear Magnetic Resonance, D. Vandeplassche et al., Physical Review Letters 57, 2641-2644 (1986).

28. Anisotropic Alpha Emission from On-Line-Separated Isotopes, J. Wouters et al., Physical Review Letters 56, 1901-1904 (1986).

Attachments

1. GSI Nachrichten 11-86 [Details of SIS-18].

2. Sudden Change in the Nuclear Charge Distribution of Very Light Gold Isotopes [title page + abstract].

3. A Shell Model Description of $0^+$ Intruder States in Even-Even Nuclei [title page].

Koeckel

# GSI 11 - 86

# NACHRICHTEN

## CALL FOR PROPOSALS AND LETTERS OF INTENT

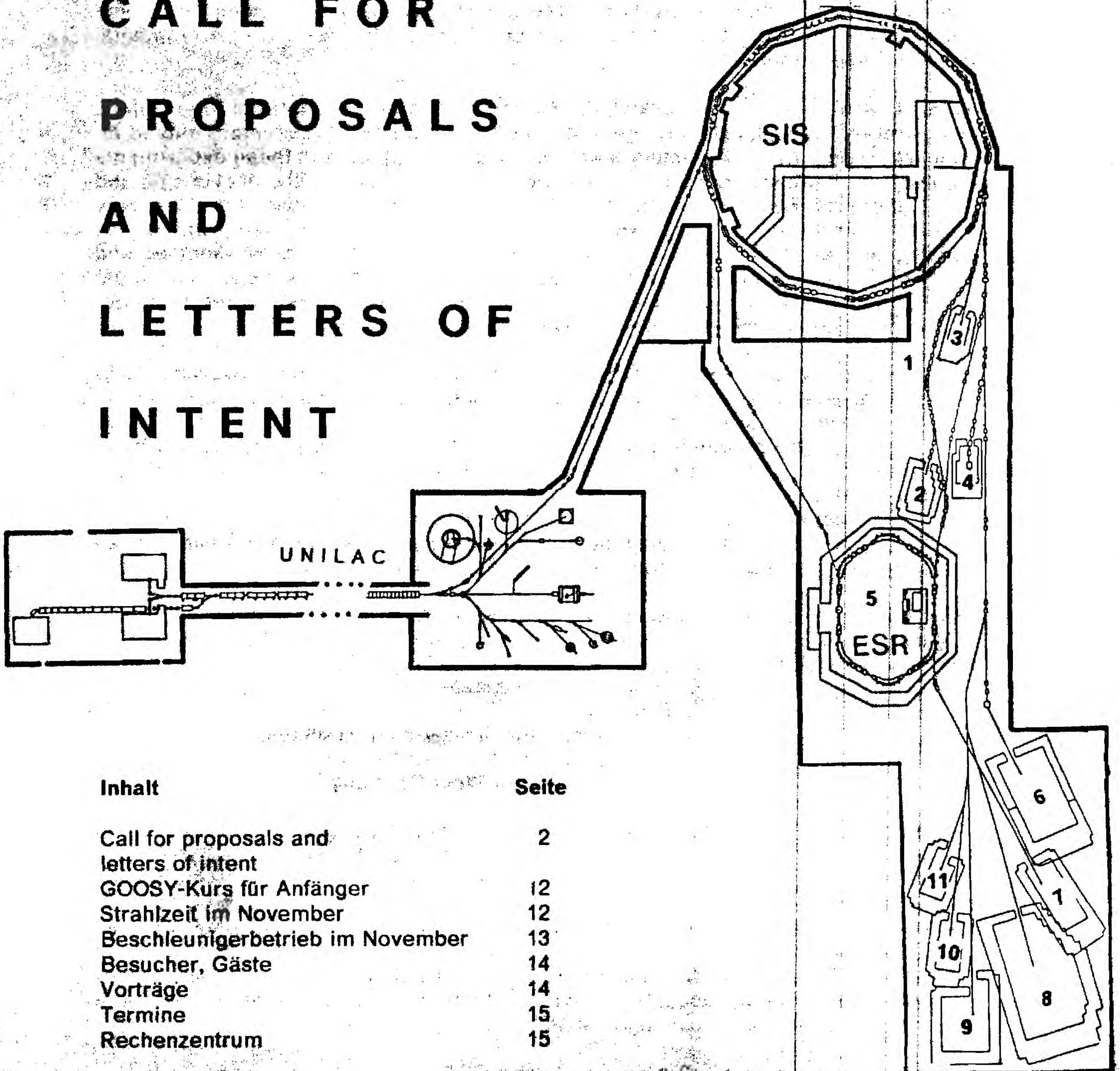


Fig. 1: Layout of SIS/ESR accelerator complex and experimental areas.



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| Call for proposals and letters of intent | 2 |
| GOOSY-Kurs für Anfänger | 12 |
| Strahlzeit im November | 12 |
| Beschleunigerbetrieb im November | 13 |
| Besucher, Gäste | 14 |
| Vorträge | 14 |
| Termine | 15 |
| Rechenzentrum | 15 |




Postanschrift: Gesellschaft für Schwerionenforschung (Mitglied der AGF)
Postfach 110 541
6100 Darmstadt

**CALL FOR PROPOSALS AND LETTERS OF INTENT FOR SIS/ESR EXPERIMENTS**

The workshops held at Rauischholzhausen and at GSI about future experiments at the heavy-ion synchrotron SIS and the storage ring ESR have confirmed the broad interest in the areas of research that can be explored with these machines. Since then these ideas have been extensively discussed in regular meetings among inside and outside scientists, so that by now some general features of necessary experimental equipment have emerged.

At this point we would like to ask you to submit proposals and letters of intent which could form the basis for the first generation of experiments. These letters should allow to assess the new information which one hopes to obtain from these experiments and also their technical feasibility. In addition they should help in the final design and specifications of the experimental facilities. For this latter purpose it will be very useful to indicate whether you want to perform your experiment using one of the currently discussed facilities, to what extent you would like them to be modified and expanded, the amount of support you expect from GSI, and to what extent you would be able to contribute to the construction of the experimental set-up and/or in the development of the necessary detector-systems, data handling etc.

In order to provide an overview of the present plans for the experimental areas at SIS and ESR, and of the beam parameters to be expected during the first years, we enclose the following information:

- technical parameters and expected performance characteristics of SIS
- technical parameters and expected performance characteristics of ESR
- design characteristics of proposed facilities at ESR
- present overall layout of the target hall
- general specification of the various experimental stations in the target hall
- performance characteristics of the fragment separator

We would like to ask you to submit your proposals and letters of intent by
**March 1, 1987**
and to address them to

**Professor Paul Kienle**
**Direktor**
**Gesellschaft für Schwerionenforschung**
**Postfach 11 05 41**
**6100 Darmstadt / West Germany**

We realize that this date does not leave time for a detailed quantitative discussion of all aspects of your proposed experiment. On the other hand we hope that this allows for sufficient time to provide us with the information needed to proceed with the detailed layout of the experimental facilities and, most important, to plan the research program for the first years. We are planning a workshop at GSI from March 30 through April 2, 1987, where the research program on the basis of these proposals and letters of intent will be discussed. A detailed announcement will follow soon. For any further information concerning proposals and letters of intent or the workshop, do not hesitate to call us or any other colleague at GSI.

F. Bosch (713), W. Henning (665/664), U. Lynen (763)

## DESCRIPTION OF ACCELERATOR FACILITIES

The figure on the front-page schematically illustrates the planned new accelerator facility with the existing UNILAC as injector and the two-ring SIS/ESR system for acceleration to relativistic energies and accumulation, storage and cooling. Also indicated is the new experimental target area. In the following, performance characteristics and technical specifications of the accelerator and design parameters of the proposed experimental facilities are summarized. In all cases, resolutions and acceptances refer to the full spread (FWHM).

### *The Heavy-Ion Synchrotron SIS*

The synchrotron has a 12-fold symmetry of the magnetic lattice with 18 Tm bending power and 216.72 m circumference. The focussing with quadrupole triplets ensures large acceptances of $A_H = 200\,\pi$ mm mrad and $A_V = 100\,\pi$ mm mrad and a momentum acceptance of $\Delta p/p = 6\,\%$ with a modest aperture of $170 \times 70$ mm². The ramprate of the dipole magnets is $\dot{B} = 10$ T/s up to 1.2 T which yields a cycleperiod of 3 Hz up to energies of 1 GeV/u (for $q/A = 0.5$), and $\dot{B} = 4$ T/s at the highest energies corresponding to 1 Hz cyclerate.

The maximum energies achievable with SIS depend on the specific charge states of the injected beam and thus on the stripping conditions during the acceleration in the UNILAC (Fig. 2). The design beam currents are shown in Fig. 3, the ion currents that can be expected during the first three years of operation in Fig 4.

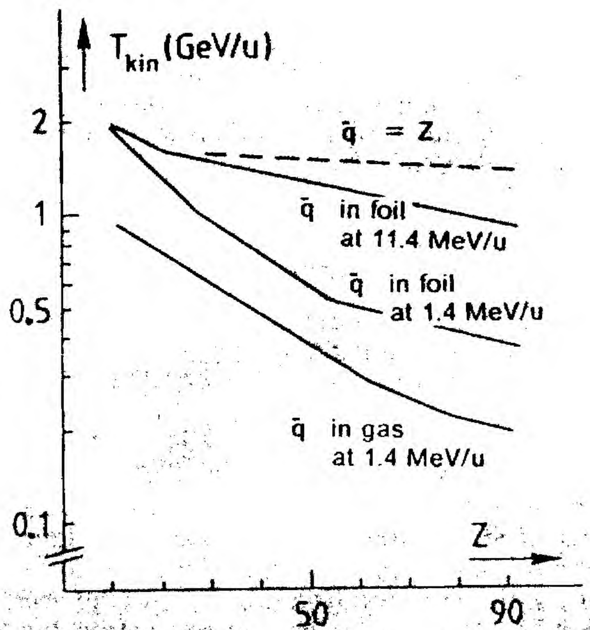


**Fig.2:** Maximum energy at SIS as a function of nuclear charge Z for various average charge states $\bar{q}$ determined by the stripping conditions in and after the UNILAC.

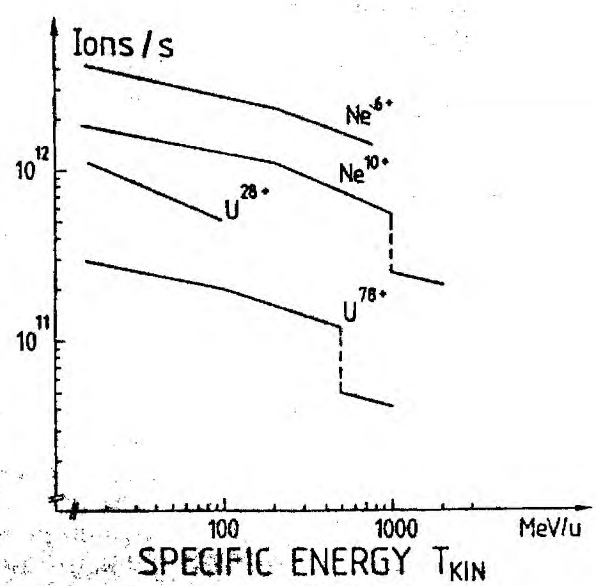


**Fig.3:** SIS design beam currents as a function of energy, for ions with low and high charge states.

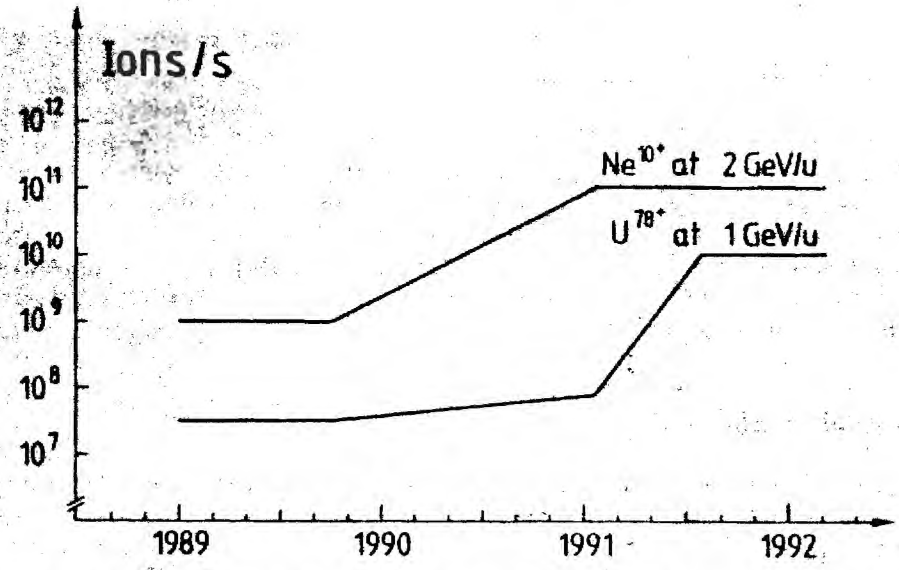


**Fig.4:** SIS ion currents for neon and uranium beams during the first three years of operation.

The momentum spread and the time structure of the circulating beam is about $\Delta p/p \cong 10^{-3}$ and $\Delta t_B = 20\text{-}40$ ns with standard acceleration. Momentum spread as well as pulse length could be reduced substantially by synchronizing SIS rf acceleration to the UNILAC micropulse structure, leading to a momentum spread in the range of $10^{-4}$ and to a pulse width below 1 ns. In this mode of operation a special rf system (9-54 MHz) would allow particle currents up to $10^{9}$-$10^{10}$ p/s. Alternatively, a special rf extraction procedure may yield $\Delta p/p = 2 \times 10^{-4}$ and $\Delta t_B = 500$ ps. A third way is the use of rf bunching in combination with electron cooling in the ESR to achieve microbunches of less than 1 ns duration and high momentum resolution ($\Delta p/p < 10^{-4}$) simultaneously.

Two systems will be installed for beam extraction from SIS: a slow extraction over 100 ms and a fast extraction that preserves the bunch structure of the beam. Additonal information about SIS can be found in an article by K. Blasche et al. (Particle Acc. Conf. 1985, Vancouver, IEEE Trans. NS 32 (1985)).

### *The Experimental Storage Ring ESR*

The main characteristics of the ESR (fig. 5) are a maximum bending power of 10 Tm, large momentum acceptance, stochastic as well as electron cooling of stored beams, and a special magnetic lattice with two magnet-free straight sections for electron-cooling and for the installation of in-ring experimental equipment.

The ESR circumferece is 108.36 m, exactly one half of SIS. The ring geometry is a stretched hexagon with six bending magnets and two long straight sections; superimposed is a focussing structure consisting of four quadrupole doublets and four triplets. In addition, pick-ups and kickers for stochastic pre-cooling as well as pick-ups for scanning the ion revolution frequency with high precision (Schottky-scan) are foreseen. Typical ESR cycles are between 2 and 12 s, including fast beam transfer and rf-stacking (0.02 s), electron cooling (0.2-0.7 s), and in-ring experiments (1-10 s).

Between SIS and ESR, the ions may be stripped once more to the highest possible charge state. For a Cu-stripper of several g/cm², an efficiency of ≈60 % for $U^{92+}$ (at 556 MeV/u) and of ≈100 % for $Xe^{54+}$ (at 609 MeV/u) is expected. Alternatively, a target can be installed for projectile fragmentation. After separation in the fragment separator, the ESR can accept these "hot" secondary beams within a large momentum band ($\Delta p/p$ = 1 % at an emittance [illegible] = 20 π mm mrad).

The ion optics of the ring allows essentially three modes of operation: At moderately modulated dispersion along the ring (optical mode I in table 1) secondary beams of large momentum spread may be accepted; at zero dispersion in the straight sections (optical mode II) multi-charge operation with $\Delta q/q = 3.4$ % is possible; at large dispersion (optical mode III) two beams of slightly different energies circulating simultaneously can be brought to intersect at a well-defined angle of about 100 mrad, corresponding to a fixed target equivalent energy of up to 7 MeV/u ("crossed beams").

The cooling devices at the ESR, stochastic and electron cooling, can complement each other. For beams of low phase space density (e. g. secondary beams), stochastic pre-cooling (with typical cooling times of about 1 s) is appropriate; for momentum spreads $\Delta p/p < 10^{-3}$, electron cooling is more efficient. For electron cooling, an effective interaction length of 2.5 m is foreseen. A "cold" parallel electron beam (typical transversal temperature < 0.3 eV) of 2-10 amperes and 5 cm diameter moves collinearly with the ion beam at the same velocity. In thermodynamical equilibrium one can expect beam emittances of about 0.1 $\pi$ mm mrad and a momentum spread $\Delta p/p$ smaller than $10^{-4}$. If the number of ions is significantly below the space charge limit, momentum spreads of $10^{-5}$ might be reached.

Electron cooling will extend the storage time during experiments with internal targets by compensating for intra-beam scattering and scattering from target nuclei. On principle, the limitation of beam life-time will be due to radiative electron capture (REC) in the cooling section. For example, for a cooled beam of $U^{92+}$ the REC-determined life-time is estimated to be ~20 s. The most severe source of beam losses in the ESR without electron cooling are charge-changing collisions with residual gas atoms. Therefore, a working pressure of $10^{-11}$ mbar for the ESR is intended. At this pressure the estimated life-time of a $U^{92+}$ beam is about 100 s at 20 MeV/u and more than 20 h at 500 MeV/u.

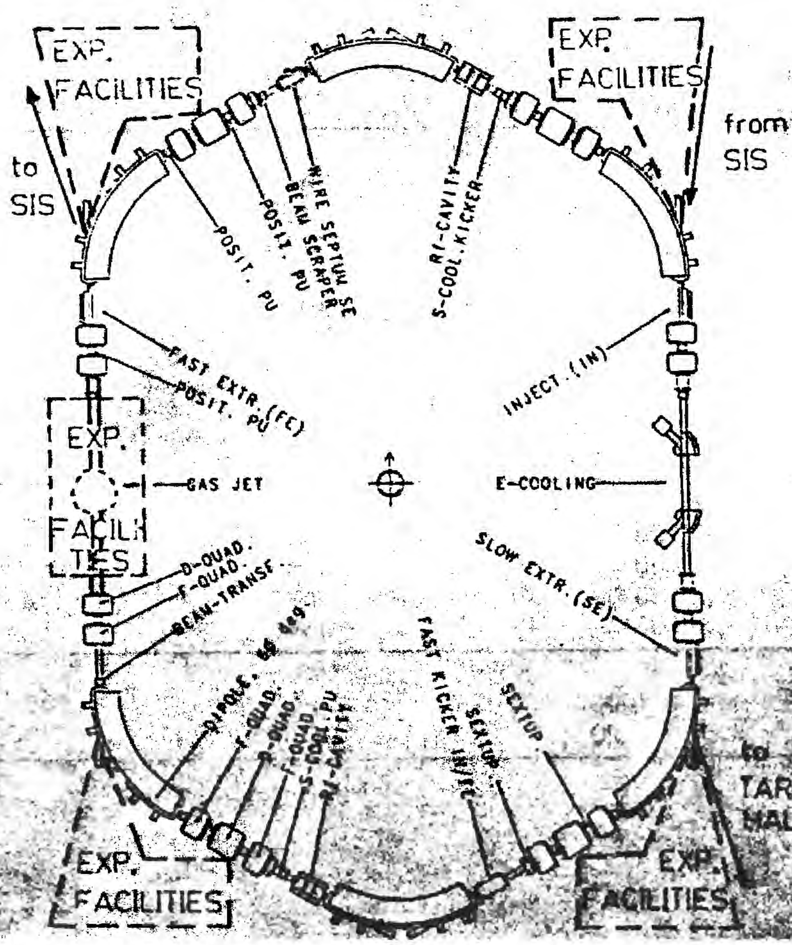


Fig.5: Layout of the ESR

The cooled beams may either serve for in-ring experiments (e. g. with internal targets) or they may be slowly extracted for target hall experiments. Alternatively, after suitable rebunching, they can be fast re-injected into SIS for acceleration or deceleration. Whereas the transverse emittances remain nearly unchanged, the momentum spread of a cooled beam is strongly increased by bunching.

In table 1 major parameters of the ESR are summarized. A more detailed description of the ESR-parameters is available upon request (GSI-ESR-TN/86-01).

**Table 1**
**ESR-Parameters**

| Ion | Specific Energy T[MeV/u] | Maximum number of stored ions at $T_{max}$ |
|---|---|---|
| p | 30 - 2200 | |
| $^{20}Ne^{10+}$ | 3.0 - 834 | $9.5 \times 10^{10}$ |
| $^{40}Ar^{18+}$ | 3.0 - 709 | $6.6 \times 10^{10}$ |
| $^{84}Kr^{36+}$ | 3.0 - 656 | $4.0 \times 10^{10}$ |
| $^{129}Xe^{54+}$ | 3.0 - 609 | $3.0 \times 10^{10}$ |
| $^{238}U^{92+}$ | 3.0 - 556 | $1.4 \times 10^{10}$ |

| | | | | |
|---|---|---|---|---|
| Magnetic rigidity | 0.5 - 10 | | | Tm |
| Ring circumference | 108.36 | | | m |
| Optical mode (see text) | I | II | III | |
| Acceptance $A_h$ ($\Delta p/p = 0$) | 411 | 383 | 554 | $\pi$ mm mrad |
| Acceptance $A_v$ ($\Delta p/p = 0$) | 163 | 164 | 170 | $\pi$ mm mrad |
| Momentum acceptance $\Delta p/p$ ($\varepsilon_h = 0$) | 72 | 80 | 68 | $10^{-3}$ |
| Working pressure | $10^{-11}$ | | | mbar |
| Baking temperatur | 300 | | | °C |
| Electron cooler | | | | |
| Effective length | 2.5 | | | m |
| Energy range(ions) | 30 - 560 | | | MeV/u |
| Energy range (electrons) | 16.5 - 310 | | | keV |
| Density | $\leq 2.10^8$ | | | $cm^{-3}$ |
| Transversal temperature | $\leq 0.3$ | | | eV |
| Current | 2 - 10 | | | A |
| Current density | 0.10 - 1.0 | | | A $cm^{-2}$ |
| Guiding field | 0.01 - 0.25 | | | T |
| Range of $\Delta p/p$ (ions) | $10^{-3}$ - $10^{-5}$ | | | |
| Range of emittance (ions) | 2 - 0.05 | | | $\pi$ mm mrad |
| Cooling time | | | | |
| $Ne^{10+}$ ( 30 MeV/u) | 125 | | | ms |
| $Ne^{10+}$ (500 MeV/u) | 630 | | | ms |
| $U^{92+}$ ( 30 MeV/u) | 30 | | | ms |
| $U^{92+}$ (500 MeV/u) | 90 | | | ms |
| Life-time of ions due to REC | | | | |
| $Ne^{10+}$ | > 1000 | | | s |
| $U^{92+}$ | 20 | | | s |

### *In-ring experiments at the ESR*

In-ring experiments are expected to cover an essential part of the experimental program at the ESR. The maximum energies - 834 MeV/u for Ne and 556 MeV/u for U - allow to investigate ions with both, high atomic charge q and high nuclear charge Z, up to $q = Z = 92$. A magnet-free straight section of 6 m length allows the installation of internal targets and detection devices.The shielding of the ESR (see fig. 1) leaves at least 5 m space for experimental equipment between beam and shielding wall and 2 m clearance above and below the beam. The beam injection from SIS as well as the beam extraction into the target hall and re-injection into SIS have been designed as to allow collinear observation along both straight sections (electron cooling and experimental section). The bending magnets after each straight section will be designed to allow measurements of charge-transfer processes. Another important feature of the ESR is the possibility of experiments with secondary, exotic nuclei delivered by the fragment separator. Mass determination with a precision of $\Delta A/A = 10^{-5} - 10^{-6}$ should be possible by a Schottky-scan at a momentum spread of $10^{-5}$ for the cooled beam.

The following permanent experimental facilities (besides the electron cooler) are being discussed:

1. An internal gas jet target with standard gases like hydrogen, nitrogen, oxygen, and noble gases. The jet diameter is between 3 and 5 mm, the speed between $10^2$ and $10^3$ ms$^{-1}$. The thickness, of the order 1 to 100 ng cm$^{-2}$, follows from the requirement that beam heating due to scattering in the target can be compensated by simultaneous electron cooling.
2. A collinear laser-resonator system at the experimental section. Its components will be separated from the UHV of the ESR by windows designed for transmission of both the primary and secondary radiation (the latter will have, for 180° re-emission and high energy beams, a quite different wavelength).
3. Ge(Li)-detectors for collinear observation of radiative electron-capture(REC) radiation in the cooler section, with special UHV windows (aperture ~4 cm). The effective solid angle for radiation originating in the electron-ion interaction region will be of the order $10^{-6}$ sr. The Ge(Li)-detectors can be exchanged with other detection devices (X-ray spectrometers, gratings, lasers, etc.).

**Data on the experimental section of the ESR**

| | | | | | |
|---|---|---|---|---|---|
| Beam height | | 2 | | | m |
| Useful length | | 6 | | | m |
| Minimum aperture | horizontal | 250 | | | mm |
| | vertical | 70 | | | mm |
| Optical mode | (cf. table 1) | I | II | III** | |
| Beam diameter* | horizontal | 9.2 | 7.6 | 0.54 | mm |
| | vertical | 13 | 13 | 2.0 | mm |
| Beam divergence | horizontal | 0.53 | 0.53 | 12.5 | mrad |
| | vertical | 0.32 | 0.32 | 2.0 | mrad |
| Internal gas jet target | species | $H_2$, He, $N_2$,$O_2$ ... | | | |
| | thickness ($H_2$) | 0.3-300 | | | ng cm$^{-2}$ |
| | diameter | 3 - 5 | | | mm |

* for $\epsilon_{h,v} = 1\,\pi$ mm mrad and $\Delta p/p = 5\times10^{-4}$ and roughly the number of stored particles listed in table 1.

** "Crossed-beam" mode. Parameters at crossing point by means of low-β-insertion quadrupoles.

## EXPERIMENTAL AREAS

Experimental stations, labeled by consecutive numbers in fig. 1, are currently planned near the SIS synchrotron, at the ESR storage ring and in the target hall. Two well-shielded caves (no. 3 and 4) are located near the synchrotron for experiments with high beam intensities and for experiments investigating high energy densities in matter. Between SIS and ESR the fragment separator (1) is located which allows experiments with rare fragments (2) and also injection into the ESR. Further experimental stations are located at the ESR (5) and in the target hall (6-11).

At present, six large experimental caves are being discussed for the target hall:
- a general purpose target station (6)
- a superconducting spectrometer with a toroidal field and large solid angle for the investigation of rare particles (mesons, leptons, possibly antiprotons) (7)
- a superconducting magnetic specrometer with large solid angle for the investigation of peripheral collisions (8)
- a $4\pi$-detector for the investigation of central collisions (9)
- a station for applied physics and biological research (10)
- and a station for atomic physics (11)

A common feature for all stations (except no. 6) is, that they operate with beams extracted either from SIS or from ESR. Therefore the standard beam height will be 2 m in all caves, unless an additional vertical deflection is installed for a given beam line. The use of parasitic beams will be possible on a pulse-to-pulse basis. In this way, the main user and the parasitic user may work with different beams and energies. Experiments using the ESR may run parallel to experiments using the extracted SIS-beam. For most experimental caves this also holds if the first experiment uses an external beam from the ESR. At present no DC beam splitting is planned. The present shielding has been designed to allow for fairly easy access to the caves even for large pieces of equipment. It probably must be increased if the highest beam intensities are used. Electronics and CAMAC-crates, together with some graphic terminals will be placed close to the experimental areas in huts not shown in the figure. The main computers for data taking will be VAX's. They will, in general, be installed at a more central location.

### *TOROID-Spectrometer*

The Toroid-Spectrometer is planned to be a large solid-angle device for the spectroscopy of light reaction products, i.e. mesons ($\pi^{\pm}$,$K^{\pm}$), leptons ($e^{\pm}$,$\mu^{\pm}$), and possibly antiprotons. The design aims for an azimuthal opening angle of about 50% through a toroidal magnetic field generated with a ring of superconducting coils. Such an arrangement has the advantage of not requiring an iron yoke to close the magnetic flux lines. An iron free design also provides for a wide dynamic range in rigidity (including e.g. low momentum $e^{\pm}$). The magnetic field produced by the superconducting coils is expected to reach 6T. Each individual segment will consist of a coil arrangement producing a field falling off more slowly than the 1/R dependence resulting from one single coil per segment (as for example in an Orange-spectrometer).

Three modes of operation are being considered:
(a) Particles with a momentum of less than ~ 700 MeV/c can be deflected by more than 90° away from the beam axis. This allows the focal plane detectors to be positioned upstream from the target and thus not exposed to the forward peaked strong background radiation. In this geometry scattering angles from 25°-80°, or (after repositioning the target) from 60°-120° are covered.
(b) High momentum ejectiles (≤ 1300 MeV/c) scattered into angles from 15° to 35° may be bent towards the beam axis and registered by detectors shielded by a

(c) For a limited angular range around 90° (± ≅30°) pairs of particles of similar momentum (≤600 MeV/c) but opposite charge may be detected in coincidence by two sets of focal plane detectors.

Good momentum resolution will be achieved by ray-tracing in tracking detectors, rather than by higher order corrections of the spectrometer ion optics. For particle identification in the focal plane, ΔE- and E-detectors will be used which should also allow to register the delayed signals from $\pi$ or K-decay or annihilation of antiprotons. The absence of a massive iron yoke allows the installation of coincidence detectors over an extended angular ange; in mode (a) or (c) a forward cone of at least ±25° remains free for the detection of e.g. heavy reaction fragments or for photon counters.

***Large Acceptance Forward Spectrometer***

This experimental set-up is primarily designed for the investigation of peripheral interactions where the relevant kinematical quantities of one or several nuclear fragments of the projectile must be determined with high precision in order to reconstruct the intermediate system. An important capability of this spectrometer is the detection of fragments emitted around 0° and their separation from the direct beam. This separation should be particularly effective for negatively charged reaction products like $K^-$ or $\bar{p}$.

The experimental set-up consists of a superconducting magnet at 0° with a large angular acceptance. Because of this, focussing can only be achieved to first order and the expected momentum resolution of $\Delta p/p \sim 10^{-3}$ will result from ray-tracing using tracking detectors. In order to detect particles with very different magnetic rigidities a C-magnet will be used. A complete particle identification will be achieved by additional charge and velocity measurements. Several target positions are foreseen in order to allow for sufficient space for additional detectors.

Specification of the spectrometer:

| | |
|---|---|
| $\int B dl$ | $\geq 6$ Tm |
| $\Delta p/p$ | $\sim 10^{-3}$ |
| $\Delta\Theta, \Delta\varphi$ | 200 mrad |
| $\Delta\Omega$ | 40 msr |
| $B\rho_{max}/B\rho_{min}$ | $> 2$ |

The development of appropriate detectors with high resolution has been started.
- A multiple sampling ionization chamber will allow to determine the trajectories and atomic numbers of several coincident fragments.
- Ring Image Cerenkov (RICH) detectors will determine the particle velocity in order to resolve individual masses even for heavy fragments with high resolution.

Other detectors presently under discussion are neutron or photon detectors as well as a target hodoscope for the detection of particles from the nuclear fireball region or fragments of the target nucleus.

***The 4π-Multidetector-Facility***

The design of a new 4π-detector facility aims at the investigation of central nucleus-nucleus collisions by extracting specific observables as well as global correlations among the reaction products on the basis of a model independent analysis of each event.

The instrument will be capable of detecting photons as well as charged particles ($\pi^{\pm}$, p, d,..., heavy clusters) in a solid angle of 4π. In the presently discussed design the apparatus comprises a central tracking detector in a solenoidal magnetic field (0.5 T), a scintillator barrel (subtending the angular range 18° to 175°), and a forward angle wall. Each of the ≅1400 barrel modules consists of a plastic scintillator sandwiched with a CsI crystal. This configuration allows a photon-charged particle identification by means of pulse shape analysis exploiting different relative intensities and decay times of the scintillation light components. For angles larger than 40° a segmented drift chamber of 80 cm diameter operated in the solenoidal magnetic field provides $\pi^+$ and $\pi^-$ identification by tracking. The forward detector is subdivided into ≅ 1200 lead glass modules each of them with a plastic phoswich detector in front for a ΔE-t identification of charged particles.

The required granularity of the apparatus has to be sufficient to handle the expected multiplicities even for U-U collisions at the highest SIS energies and to detect single photons as well as to reconstruct neutral pions. The dynamic range of the device should be able to perform reaction studies over the full energy range from 0.1 to 2.0 GeV/u.

***Separator for Projectile Fragments***

With the relativistic heavy-ion beam from SIS, energetic radioactive beams of exotic nuclei can be produced by projectile fragmentation or electromagnetic dissociation. The reaction products are emitted into a narrow angular cone in beam direction with velocities close to that of the projectiles. The separated exotic nuclei can be implanted into detectors for nuclear spectroscopy, into solids or biological samples for material science, solid-state, or applied research. Moreover, it is planned to inject the separated beams into the ESR, where they are available for experiments, if necessary after cooling. It is also possible to decelerate the ions to energies near the Coulomb barrier.

The separator between SIS and ESR (1 in fig. 1) is an achromatic magnetic deflection system with an absorber located at its dispersive symmetry plane. Due to the reaction kinematics the first stage selects a certain momentum to charge ratio. In the second stage the separation depends on the velocity change in the absorber, determined predominantly by the nuclear charge Z. The separator is designed to handle all isotopes up to uranium. It can also be operated in an energy-loss mode with a resolution of $p/\Delta p \geq 2 \times 10^{3}$, if second order aberrations are corrected. With a typical target thickness of 1 g/cm$^2$ of Al, radioactive beams of up to $10^8$/s are expected for isotopes close to the projectile; intensities for nuclei at the limits of the known isotopes are expected to be much smaller but still sufficient for nuclear spectroscopy.

The design specifications are:

| | |
|---|---|
| $B\rho_{max}$ | 18 Tm (0.1 - 1 GeV/u) |
| angular acceptance horizontal | 10 mrad |
| angular acceptance vertical | 20 mrad |
| momentum acceptance $\Delta p/p$ | 2 % |
| overall efficiency | ~ 0.6 |
| resolution ($B\rho/\Delta B\rho$) | $\geq 2\times10^3$ |
| mass resolution ($M/\Delta M$) | > 200 |
| charge resolution ($Z/\Delta Z$) | > 90 |

A more detailed description of the fragment separator is available upon request (G. Münzenberg, GSI).

***Irradiation Facilities at SIS***

Two target stations are under discussion for irradiation experiments in biology and medicine, chemistry and nuclear track research. At a location near SIS (2 in fig. 1) the full beam intensity will be available for high dose irradiations, and in the target hall (10) beams from both SIS and the ESR with up to $10^9$ part/sec can be used. A magnetic deflection system is planned for the target hall to provide a large beam spot with a uniform intensity distribution over an area of 20 x 20 $cm^2$, divided into 20 x 20 pixels.

For biology experiments, a rotating sample wheel will hold up to ten samples to be exposed to the beam sequentially. For lower beam energies between 20 and 100 MeV/u, the existing exposure set-up BIBA will be adapted. In both cases, the exposed area will be limited to $10\times10$ $cm^2$. For nuclear track research, a facility is proposed in which samples can be irradiated for exposure times as short as 2 seconds in a controlled gas atmosphere and with a well-defined angle between the sample and the beam direction.

For radiochemical experiments, a set-up is proposed which in essence consists of several small, cubic scattering chambers attached to each other, each having sides of about 750 mm length. Also planned are a fast gas-jet system for transport of short-lived reaction products ($T_{1/2} \geq$ 1s) to an on-line chemistry set-up or directly to an apparatus for spectroscopy of nuclear decays, and a rotating catcher-wheel for the study of millisecond isotopes.

## GOOSY-KURS FÜR ANFÄNGER

Vom 19. - 23. Januar 1987 findet im Seminarraum/Theorie der GSI ein Anfängerkurs für künftige Benutzer des neuen Datenaufnahmesystems GOOSY statt. Der Kurs wird jeweils vormittags von 9.30 - 12.00 Uhr und dann nochmals nachmittags von 14.00 - 16.30 Uhr gehalten, um Terminschwierigkeiten der Teilnehmer zu umgehen. Der Kurs wird sowohl eine kurze Einführung in die Bedienung der VAX (Kommandosprache, Editor, Filesystem, etc.) als auch in die Benutzung von GOOSY (Kommandosprache, Analyse, Datenbasis, Display, CAMAC) umfassen. Es wird gebeten, sich bei H. Essel (Tel. 491) oder M. Richter (394) anzumelden.

Der Kurs ist **nur** für Benutzer von GOOSY gedacht, er dient nicht einer allgemeinen Einführung in die VAX-Benutzung.

## STRAHLZEIT IM NOVEMBER

| Exp. Nr. | Experiment-Kurzbezeichng. | Ionensorte | Energie MeV/u | Meßplatz | Intensität TnA | Std.auf Target | Sprecher |
|---|---|---|---|---|---|---|---|
| Beschleunigerexperimente | | | | | | 2.0 | |
| 232 | Coulombanregung | $^{208}$Pb | 4.8 | X7 | .2- .4 | 44.8 | Zimmermann |
| *377 | Complex Fragm. | $^{208}$Pb | 4.8 | Z6 | .1 | 44.8 | Wozniak |
| Bio | Biologie | $^{139}$La | 14.6 | Z0 | .2 | 10.8 | Kraft |
| *KSP | Kernspuren | $^{139}$La | 14.6 | X0 | .2 | 36.2 | Spohr |
| *377 | Complex Fragm. | $^{139}$La | 17.6-18.3 | Z6 | .1- 2.1 | 77.5 | Wozniak |
| *270 | Coulombanregung | $^{139}$La | 14.6-18.0 | XK | .1- .2 | 7.1 | Günther |
| *363 | Dielektr.Rekomb. | $^{139}$La | 18.0-18.3 | X4 | .1- .2 | 12.8 | Reusch |
| 363 | ″ ″ | $^{74}$Ge | 12.6-18.6 | X4 | .1-10.3 | 98.4 | ″ |
| *383 | Contemp.$^{41}$Ca conc. | $^{74}$Ge | 13.0 | Z1 | .3- 1.0 | 16.4 | Steinhof |
| 263 | Formänderung | $^{74}$Ge | 13.8 | X4 | .9 | 7.9 | Emling |
| 201 | Laserspektrosk. | $^{16}$O | 9.5 | Y5 | 60-300 | 22.2 | Huber |
| *232 | Coulombanregung | $^{16}$O | 9.5 | X7 | .4- 30.0 | 5.9 | Zimmermann |

* Diese Experimente wurden nach Strahlteilung mit einem parasitären Strahl durchgeführt.

Die Werte sind den Wochenbilanzen der UNILAC Operateure entnommen. Diskrepanzen zwischen den hier gemachten Eintragungen, speziell der Strahlzeit und denen der einzelnen Experimentatoren sollten sofort an den Strahlzeitkoordinator gemeldet werden.

## BESCHLEUNIGERBETRIEB IM NOVEMBER

Nach dem großen Shut-Down im Oktober begann die Strahlzeit im November in der KW 46. Da nicht alle Arbeiten planmäßig abgeschlossen wurden, war der Strahlbetrieb in den ersten drei Tagen stark behindert. Die Strahlzeit begann am 13.11.86 mit Sauerstoff und 9,6 MeV/u in Y7. Anschließend wurde auf $^{208}Pb$ und 4,75 MeV/u für Meßplatz X7 umgestellt. Da dieses Experiment vorzeitig beendet wurde, begann die $^{139}La$-Strahlzeit früher als geplant. Die angestrebte Endenergie von über 18 MeV/u konnte zunächst nicht erreicht werden, da das neue Netzgerät von Alvarez 4 noch Anlaufschwierigkeiten hatte. Erst nach einer größeren Reparatur konnte am 21.11.86 auf 18 MeV/u umgestellt werden. Mit dieser Energie wurden die Experimentierplätze Z6, X0, XK und X4 beliefert.
Am 24.11.86 wurde dann für den Rest der Strahlzeit auf $^{74}Ge$ für X4 umgestellt. Es wurden verschiedene Energien zwischen 12 und 18 MeV/u eingestellt. Diese Strahlzeit verlief recht befriedigend.
Am 29.11.86 wurde dann planmäßig die Maschine abgeschaltet.

| Einschalt-zeit | Beschl. Entw. | Quellenserv. und Wartung | Einstell-zeit | Ausfall-zeit | Beschl. Exp. | Target-zeit | Paras. Strahl |
|---|---|---|---|---|---|---|---|
| 472 h | 79.3 h | 21.9 h | 43.0 h | 64.1 h | 02.0 h | 261.7 | 123.2 h |

D. Wilms (Tel. 340)

### Korrektur

Bei dem Aufruf zur Mitarbeit am Scientific Report 1986 ist ein Fehler in der angegebenen Telefonnummer enthalten. Die Nummer muß heißen: **06151 359610.**

## BESUCHER IM NOVEMBER

| | |
|---|---|
| 10.11. | Prof. Brody, Weizmann Institute, Rehovot, Israel<br>Betreuer: S. Glückert |
| 10.11.-14.11. | S. Mahmoud, University of Jordania, Amman, Jordania<br>Betreuer: H. Folger |
| 11.11. | Fr. H. Hodde, Kernphysik, Universität Bonn<br>Betreuer: H. Folger |
| 13.11. | A. Meens, F. Kunz, CRN, Strasbourg, France<br>Betreuer: H. Folger |
| 21.11. | W. Gentzsch, Regensburg<br>Betreuer: S. Glückert |
| 17.11. | M. Durand, ISN, Grenoble, France<br>Betreuer: W. Nörenberg |
| 17.11.+18.11. | N. Takahashi, Osaka University, Japan<br>Betreuer: W. Trautmann |
| 24.11.-28.11. | M. Sambatero, Ist. Naz. di Fisica Nucl., Catania, Italy<br>Betreuer: W. Nörenberg |
| 26.11.-28.11. | B. Schürmann, TU München<br>Betreuer: W. Nörenberg |
| 27.11.-15.12. | J.L. Wood, Georgia Inst. of Technology, Atlanta, USA<br>Betreuer: E. Roeckl |
| 03.12. | D. Guillemaud-Mueller, A.C. Mueller, GANIL, Caen, France<br>Betreuer: E. Roeckl |
| 16.-20.12. | R. Broglia, Istituto di Science Fisiche, Milano, Italy<br>Betreuer: W. Nörenberg |

## VORTRAEGE

15.30 Uhr mit Tee — Hörsaal: GSI-Kolloquium

| | |
|---|---|
| 09.12. | J.L. Wood, Georgia Inst. of Techn., Atlanta, USA<br>"New Developments in Nuclear Shape Coexistence" |

10.00 Uhr — Seminarraum (Südbau, II. Stock): Doktoranden-Seminar

| | |
|---|---|
| 09.12. | J. Knoll, GSI<br>"Informationstheorie und Statistik" |
| 16.12. | P. Grimm, GSI<br>"Vergleich der $\pi^0$- und $\gamma$-Emission in Schwerionen-Stößen bei mittleren Energien" |
| 06.01. | R. Künkel, GSI<br>"Nukleonen-Paartransfer" |

**TERMINE**

| | |
|---|---|
| 12.12. | Aufsichtsratsitzung |
| 17.12. | Forschungsseminar |
| 24.12.-einschl.02.01. | arbeitsfreie Zeit bei GSI |

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+--------------------------------+
!                                !
!   R E C H E N Z E N T R U M    !
!                                !
+--------------------------------+
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Betriebsdaten der Rechenanlagen im NOVEMBER 1986 (Zeit in Stunden)

| Rechner | geplante Einschalt-zeit | vorsorgl. Wartung Hardware | Wartung Software Testzeit | System Neu-start | Ausfall Hardw./ Soft. | Ausfall Klima/ Strom | Stillstand Nachts/ Wochenende | geplante Produkt.-Zeit | erreichte Produkt.-Zeit |
|---|---|---|---|---|---|---|---|---|---|
| 3090-MB | 744.1 | - | - | 0.3 | - | - | - | 744.1 | 743.8 |
| | 100.0% | - | - | - | - | - | - | 100.0% | 99.9% |

Betriebsstörungen (Zeitangaben in Stunden)

| Rechner | Anzahl ungeplante Neustarts | mittlerer Abstand Neustarts | kürzester Abstand Neustarts | längster Abstand Neustarts | Anzahl VTAM Neustarts |
|---|---|---|---|---|---|
| 3090-MB | - | - | - | - | - |

Es wurden insgesamt 29.298 Stapelaufträge (im Mittel 945 täglich) und 18.866 Sitzungen am Dialogsystem TSO (im Mittel 608 täglich) bearbeitet.

S.Glückert, Tel. 527

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/86-174
6 January 1987

# SUDDEN CHANGE IN THE NUCLEAR CHARGE DISTRIBUTION OF VERY LIGHT GOLD ISOTOPES*

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J. Campos[2] and A. Rodriguez Yunta[2]
M.J.G. Borge[3-c] and A. Venugopalan[3-b]
J.L. Wood[4] and R.B. Moore[5]

and

the ISOLDE Collaboration, CERN, Geneva, Switzerland

Submitted to Physical Review Letters
Geneva, January 1987

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Pt isotopes[16]. In the neighbouring odd-proton nuclei (Au and Tl isotopes) the shape coexistence is associated with shell-model intruder states[13]. In particular, the $\pi h_{9/2}$ intruder orbital becomes the ground-state configuration in $^{185}$Au (the spin-5/2 band member is the observed ground-state spin due to particle-core decoupling[17,18]), whereas in the odd-mass Tl isotopes the $\pi h_{9/2}$ intruder state remains an excited state. For the latter case, isomerism results from this 9/2 state, which has been studied recently by laser spectroscopy[19]. It thus became interesting to extend the IS studies to neutron-deficient gold isotopes. In a preceding experiment[20] the IS's of $^{197-190}$Au were determined using semi on-line laser-induced fluorescence spectroscopy.

The present experiment was designed to investigate still shorter-lived Au isotopes and to determine their IS's, which represent the most straightforward and model-independent signature for shape transitions or shape coexistence. The Au isotopes were produced at the ISOLDE mass separator at CERN. Since no target and ion-source system presently exists for a direct production of Au isotopes, these nuclei had to be obtained as daughters of Hg isotopes which could be produced with yields up to $10^{10}$ atoms per second per mass number by a Pb(p,3pxn)Hg spallation reaction[21]. The technique of resonance ionization spectroscopy (RIS)[22,23] was used and combined with time-of-flight (TOF) mass spectroscopy in order to determine the hyperfine structure (HFS) and IS in the $D_1$ line of the very neutron-deficient Au isotopes. Because of the short half lives and the small production rates of the Au isotopes far off stability, the investigations had to be performed on line using the ISOLDE facility. Alkhazov et al.[24] performed the first on-line RIS experiment on short-lived isotopes. The pres-

370 358 1 40 27 Galley 1

370358 North Holland Nuclear Phys. A Gal. Gal. 1 Fol. 1 K27

Nuclear Physics A000 (1987) 000–000 MS 358

North-Holland, Amsterdam

# A SHELL-MODEL DESCRIPTION OF $0^+$ INTRUDER STATES IN EVEN–EVEN NUCLEI

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Received 29 September 1986

**Abstract:** Starting from the nuclear shell structure in medium-heavy and heavy nuclei, the excitation energy for low-lying $0^+$ intruder states is studied. Taking as a simplified model two particle–two hole (2p-2h) excitations across closed shells, the effects of the pairing and the proton–neutron (monopole and quadrupole component) residual interaction on the unperturbed ~~energy~~ are calculated. Application to major closed-shell ($Z = 50$, $Z = 82$) and to subshell ($Z = 40$, $Z = 64$) regions is performed. We especially concentrate on $0^+$ intruder states in the even–even Pb nuclei. ; delete

energies

## 1. Introduction

In nuclei, the major part of the nucleonic motion is approximated by the average single-particle field. This field approximation implies the existence of magic numbers, i.e. 2, 8, 20, 28, 50, 82, 126, that give extra stability for the particular nuclei having proton and/or neutron number equal to such magic numbers. The energy separation between the last filled single-particle orbitals and the lowest unfilled orbital at magic numbers is found to vary empirically from $\simeq 10$ MeV (light nuclei) to $\simeq 3.5$ MeV ($Z = 82$ gap). Besides, a number of subshell closures have now been established, i.e. $Z = 40$, 64. In these cases, a smaller energy gap of 1 and 2.5 MeV, respectively, is observed. It is precisely the existence of closed-shell configurations that makes the study of nuclear structure approximately tractable. Most nucleons can be considered to contribute to the "core" of the nucleus and thus to the average field, leaving only a small number of nucleons, called valence nucleons (particles or holes) outside closed shells (see fig. 1). ~~In region I only~~ a few valence nucleons are present ■: Most

new paragraph

with reference to fig 1 in

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# NUCLEAR STRUCTURE FROM RADIOACTIVE DECAY

Annual Progress Report

U. S. Department of Energy

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## 1.0 Introductory Overview

The most notable development this year has been a promising step toward a quantitative description of intruder states and shape coexistence in nuclei. This idea is based on the unified view of shape coexistence that has already been proposed in qualitative form by the author. This work is being done in collaboration with K. Heyde and P. van Isacker (Institute of Nuclear Physics, Gent, Belgium) for which a NATO grant has been awarded to the author and K. Heyde.

Experimentally, there is an emerging picture of a new class of nuclear structure which is associated with intruder states and shape coexistence and occurs at low energy near a closed shell when the number of active nucleons of the other type is maximal. Confirmation of this has come from studies at UNISOR of odd-mass Tℓ isotopes for which data analysis is in progress (and see E. F. Zganjar, *et al.*, Bull. Am. Phys. Soc. 29, 1049 (1984)). Thus, we see coexisting bands resulting from the couplings $\pi s_{1/2}^{-1} \otimes$ Pb, $\pi h_{9/2}^{+1} \otimes$ Hg and $\pi j^{-1} \otimes$ Pb (deformed) in $^{189,191}$Tℓ. (The deformed states in the neutron-deficient Pb isotopes, coexisting with the spherical ground states, were recently found by the LISOL separator group - P. van Duppen, *et al.*, Phys. Rev. Lett. 52, 1974 (1984)).

Experiments at UNISOR have focused on shape coexistence, and at the time of writing, runs are scheduled (in October) to search for strongly deformed states in the very neutron-deficient Pt isotopes (to map the $N < 104$ boundary of shape coexistence near $Z = 82$) and to confirm and extend information on strongly deformed states in the very neutron-deficient Pb isotopes. Proposed studies of coexisting structures in $^{185}$Au (and see below) also have been approved along with in-beam gamma-ray spectroscopy studies of the very neutron-deficient Pb isotopes (to see rotational bands to high spin), which will be done at the HHIRF.

The first successful run at TRISTAN was conducted in July. This focused on shape coexistence in $^{120}Sn$. Radioactive sources of $^{120}In$ and $^{120}Cd$ were separated using the FEBIAD ion-source for this purpose. The $^{120}Cd$ populates $^{120g}In(J^{\pi} = 1^{+})$ which in turn populates low-spin levels in $^{120}Sn$. A considerably improved decay scheme for $^{120g}In$ has been constructed. Further and much more detailed studies are planned using the TRISTAN high-temperature ion source which is greatly superior to the FEBIAD ion source for In and Cd.

Analyses of data on the $^{187m,g}Hg \rightarrow {}^{187}Au$ and $^{191m,g}Hg \rightarrow {}^{191}Au$ decay schemes have been major areas of activity this year. The $^{191}Au$ level scheme construction has proceeded steadily and is a collaboration with the Kool on-line nuclear orientation facility at LISOL to test dynamical spinor symmetries in this nucleus. The $^{187}Au$ level scheme construction has demanded great effort. This is, in part, because of the extreme complexity resulting from <u>four</u> different shapes in $^{187}Au$. However, great care has been necessary in addition because it has been reported (C. Bourgeois, *et al*., Nucl. Phys. <u>A386</u>, 308 (1982)) that very strongly internally converted transitions in $^{185}Au$ may be of M1 multipolarity: we have been able to show that <u>all</u> the very converted transitions in $^{187}Au$ are E0 + M1 (+ E2) and are a crucial clue to shape coexistence. A proposal to make a very detailed restudy of $^{185}Au$ at UNISOR with radioactive sources of $^{185m,g}Hg$ has been approved (see also above). The study of the $^{187}Au \rightarrow {}^{187}Pt$ decay scheme was published in <u>Nuclear Physics A</u>.

The first part of the program to study shape coexistence in nuclei is completed. The review of coexistence in odd-mass nuclei (in collaboration with K. Heyde and coworkers (Gent) and R. A. Meyer (LLNL)) was published in <u>Physics Reports</u>. Data on coexistence in even-mass nuclei have been summarized in a series of papers by the author, variously appearing in conference proceedings and a publication in Nuclear Physics A. These latter investigations have been part of a program to identify and survey low-energy degrees of freedom that lie outside of the model space of the interacting boson model (IBM). The "shape coexistence" part of this program has been completed with the above mentioned publications. Detailed calculations and predictions are now being made within an extended IBM for shape coexistence (following P. Duval and B. R. Barrett, Phys. Lett 100B, 223 (1981)). This follows the initial detailed test of the Duval-Barrett model for the nucleus $^{114}$Cd which was published in Nuclear Physics A. The eventual aim of this part of the program is a review of shape coexistence in even-mass nuclei.

Considerable progress has been made in a study of particle-core coupling in odd-mass nuclei as a means of ascertaining the reliability of IBM core descriptions. This program uses the Dönau-Frauendorf model (F. Dönau and S. Frauendorf, Phys. Lett. 71B, 263 (1977).) Our initial investigations have focused on the coupling of proton or neutron particles or holes to Hg cores. The first results indicate that this approach is more sensitive to IBM parameters than the usual comparison with data on energies and matrix elements for doubly-even nuclei. This work is being done in collaboration with G. Leander (UNISOR) and P. Semmes (School of Chemistry, Georgia Tech).

Other activities have included the election of the author to the executive committee of the Holifield Heavy-Ion Research Facility (HHIRF); seminars and colloquia at the University of Kentucky, the University of Pennsylvania, the University of Toronto, Rutgers University, Drexel University, Florida State University and Chalk River Nuclear Laboratories; and invited talks/papers at the 187th Meeting of the American Chemical Society in St. Louis, the International Symposium on In-Beam Nuclear Spectroscopy in

Debrecen (Hungary), the International Workshop on Interacting Boson-Boson and Boson-Fermion Systems in Gull Lake (Michigan), the TRIUMF-ISOL Workshop in Mt. Gabriel (P. Quebec), the International Symposium on Nuclear Orientation and Nuclei Far From Stability in Leuven (Belgium) and the 7th International Conference on Atomic Masses and Fundamental Constants, Darmstadt-Seeheim (West Germany). In addition, work has continued on the description of octupole bands in rare earth nuclei using an f boson coupled to the s,d-boson cores of the IBM: this work is in collaboration with B. R. Barrett and A. Barfield (Univ. of Arizona); and groundwork has been laid on broken-pair states and new degrees of freedom above $\sim$ 2 MeV in the Sn (and Cd, Te isotopes). Finally, a short communication on intruder states and the octupole degree of freedom in the N = 83 isotones was published in Physics Letters B. This work was in collaboration with K. Heyde and coworkers (Gent) and R. A. Meyer (LLNL).

## 2.0 Experimental Program

A major area of activity is the study of neutron-deficient nuclei around the Z = 82 shell closure, with special emphasis on the levels of the odd-mass Pt, Au, Hg, Tl and Pb isotopes. A crucial ingredient of this work is the systematic investigation of low-energy structural features of sequences of isotopes (and isotones) over many adjacent mass numbers. This has a two-fold purpose. First, it enables us to build up a very complete picture of the nuclear structure that connects the regions of stable nuclei (where e.g., transfer reactions and Coulomb excitation permit the measurement of detailed spectroscopic properties) with regions far from stability, where detailed spectroscopic information is very limited. Second, it provides a map of the excitation degrees of freedom as a function of the changing proton and neutron number over broad mass regions. The mass region under study possesses the richest variety of nuclear excitations observed anywhere on the mass surface. It is intersected by the Z = 82 shell closure, and bounded by the strongly deformed nuclei with $Z \leq 76$ and the N = 126 shell closure. Between Z = 76 and Z = 82 there is a shape transition from strongly deformed prolate axial symmetry through oblate axial asymmetry to spherical symmetry. This transition has alternatively been described in terms of the interacting boson approximation (IBA) as a transition from the SU(3) through the O(6) limiting algebraic symmetries of the IBA Hamiltonian. Finally, and most dramatically of all, an island of ground state deformation has been established adjacent to the Z = 82 closed shell for the very neutron-deficient isotopes of Hg and Pt. This deformation is now understood in terms of proton intruder orbitals which give rise to the large deformation ($\beta \sim 0.27$) through an increased proton valence space and the proton-neutron residual interaction.

## 2.1 Odd-Mass Au Decays

The stuudy of the $^{187}Au \rightarrow {}^{187}Pt$ decay scheme has been published in Nuclear Physics A.

At the time of writing, a run is scheduled (in October) to search for strongly deformed states in the very neutron-deficient Pt isotopes (to map the $N < 104$ boundary of shape coexistence near $Z = 82$). Previous attempts to make these studies were seriously limited by available beam energies at HHIRF. This problem has now been overcome. This work is being done in collaboration with E. F. Zganjar (LSU) and C. R. Bingham (U. Tenn.).

The study of the $^{189}Au \rightarrow {}^{189}Pt$ decay scheme has been temporarily halted due to the heavy experimental load in other areas.

## 2.2 Odd-Mass Hg Decays

The main area of data analysis this year has been on the $^{191m,g}Hg \rightarrow {}^{191}Au$ and $^{187m,g}Hg \rightarrow {}^{187}Au$ decay schemes. The study of excited states in $^{191}Au$ is a collaboration between UNISOR and the KOOL on-line low-temperature nuclear orientation facility at the Leuven Isotope Separator On Line (LISOL) operated at the CYCLONE cylotron in Louvain-la-Neuve, Belgium. The analysis of the UNISOR $\gamma$-$\gamma$ coincidence data and level scheme construction is essentially complete. The orientation data are being analyzed. The latter data will provide unique spin assignments to excited states and accurate transition multipolarities. This work has two goals: to provide benchmark spin information in odd-mass Au nuclei far from $\beta$ stability and to determine the validity of a dynamical supersymmetry classification for levels and electromagnetic transitions in $^{191}Au$. This work is a collaboration of Georgia Tech School of Physics (principal investigators), LSU, Vanderbilt and UNISOR staff together with K. Krane (Oregon State University, Corvallis) and L. Vanneste, M. Huyse and coworkers (Katholieke Universiteit, Leuven, Belgium).

Progress on elucidating the very complex $^{187m,g}Hg \rightarrow {}^{187}Au$ decay schemes continues. An exhaustive analysis of running $\gamma$-$\gamma$ and e-$\gamma$ coincidence gates is near completion - this provides a new method of extracting $\alpha_K$ conversion coefficient information for closely spaced lines (the alternative would be ultra high resolution very low efficiency spectrometers that require very long running times). As a consistency check, absolute coincidence intensities have also been extracted for all assigned transitions. As already noted, the extreme complexity of $^{187}Au$ results from four different shapes in $^{187}Au$. In addition, as pointed out above, great care has been necessary in the analysis because it has been reported (C. Bourgeois, *et al*., Nucl. Phys. A386, 308 (1982)) that very strongly internally converted transitions in $^{185}Au$ may be of M1 multipolarity. We have been able to show that all the very converted transitions in $^{187}Au$ are E0 + M1 (+ E2). This work is in collaboration with E. F. Zganjar (LSU).

A proposal to make a very detailed restudy of the $^{185m,g}Hg \rightarrow {}^{185}Au$ decay schemes at UNISOR has been approved. This will answer the questions of what underlies the very converted transitions (see above) in $^{185}Au$. This will be a collaboration with E. F. Zganjajr (LSU), L. L. Riedinger and coworkers (Univ. of Tenn.) and G. Leander (UNISOR), and will also address the excess of bands (shape coexistence?) observed at low energy in $^{185}Au$ by in-beam $\gamma$-ray spectroscopy (A. J. Larabee, *et al*., Bull. Am. Phys. Soc. 29, 1049 (1984)).

The work on the larger paper describing the structure of the odd-mass Au isotopes has been temporarily halted because of the heavy work load in other areas.

### 2.3 Odd-Mass Tl Decays

The elucidation of the $^{187m,g}Tl \rightarrow {}^{187}Hg$, $^{189m}Tl \rightarrow {}^{189}Hg$ and $^{191m}Tl \rightarrow {}^{191}Hg$ decay schemes has been temporarily halted because of the heavy work load in other areas. Consequently, the study of the $i_{13/2}$ band systematics in $^{187-197}$Hg is also "on hold", however, see Section 3.0.

2.4 Odd-Mass Pb Decays

A major advance has been made in the understanding of the $^{189,191}$Tl level schemes. Systematics of the heavier odd-mass Tl isotopes reveals additional new bands of states at low energy in $^{189,191}$Tl. As noted above, we interpret these bands as resulting from the couplings $\pi j^{-1} \otimes$ Pb (deformed). The extraordinarily low-energy of these bands (460 keV band head in $^{189}$Tl) had been a serious puzzle until the recent location in $^{192}$Pb of a deformed band at 770 keV (P. van Duppen, et al., Phys. Rev. Lett. 52, 1974 (1984)). The work continues with analysis of new data on the $^{191m}\text{Pb} \rightarrow {}^{191}\text{Tl}$ and $^{193m}\text{Pb} \rightarrow {}^{193}\text{Tl}$ decay schemes. A preliminary communication on $^{187,189,191}$Tl has been made (E. F. Zganjar, et al., Bull. Am. Phys. Soc. 29, 1049 (1984)). This work is in collaboration with E. F. Zganjar (LSU) and ($^{193}$Tl) C. R. Bingham and coworkers (U. Tenn.). The $^{189}$Tl Study also involves the GSI, Darmstadt separator group.

2.5 Bi Decays and Deformed States in the Neutron-Deficient Pb Isotopes

Following the very recent report (P. van Duppen, et al., Phys. Rev. Lett. 52, 1974 (1984)) of strongly deformed bands in $^{192-198}$Pb, observed in the β-decay of the corresponding Bi isotopes at the LISOL facility, we have had beam time approved (for October) to study the $^{190}\text{Bi} \rightarrow {}^{190}\text{Pb}$ and $^{192}\text{Bi} \rightarrow {}^{192}\text{Pb}$ decay schemes at UNISOR. These studies will confirm and extend the above reported structures. This work is in collaboration with E. F. Zganjar (LSU) and C. R. Bingham (U. Tenn.).

In addition, a proposal to search for high-spin deformed states in $^{190,192}$Pb by in-beam γ-ray spectroscopy at HHIRF has been approved. This work is in collaboration with E. F. Zganjar (LSU), and Vanderbilt Univ. and will complement the Bi decay studies.

## 2.6 The Decay of $^{120m_1,m_2,g}In \rightarrow {}^{120}Sn$

As already noted, the first successful run at TRISTAN was conducted in July and was a study of the $^{120}Cd \rightarrow {}^{120}In \rightarrow {}^{120}Sn$ and $^{120m_1,m_2}In \rightarrow {}^{120}Sn$ decays. Radioactive sources of $^{120}In$ and $^{120}Cd$ were separated using the FEBIAD ion source for this purpose. The $^{120}Cd$ populates $^{120g}In$ ($J^{\pi} = 1^{+}$) which in turn populates low-spin levels in $^{120}Sn$. A considerably improved decay scheme for $^{120g}In$ has been constructed (many γ-ray lines assigned to $^{120}Cd$ decay -- see Nuclear Data Sheets -- have been reassigned to $^{120g}In$ decay). Further and much more detailed studies are planned using the high-temperature ion source which is greatly superior to the FEBIAD ion source for In and Cd. The aim of these studies is to locate the shape coexisting states and the zero-, one- and two-broken-neutron-pair states in $^{120}Sn$. This will constitute part of the Ph.D. thesis work of Mr. C. Papanicolopulos.

## 2.7 Other Decay Scheme Studies

The study of the $^{201m,g}Po \rightarrow {}^{201}Bi$ decay schemes is being prepared for publication. This work is being done in collaboration with R. A. Braga (School of Chemistry, Georgia Tech). The study of the $^{188}Tl \rightarrow {}^{188}Hg$ decay scheme is in press with Physical Review C. This work was a large collaboration of UNISOR members.

## 3.0 Nuclear Systematics and Models

The major activity on this contract in the past year has continued to be the program of development of nuclear systematics and models for a better understanding of nuclear structure. At a time when the ability to generate experimental data has become enormous and the manpower available to reduce these data and extract information on nuclear structure has become extremely limited - severe constraints are needed on which topics are chosen for experimental study. The author regards the development of nuclear systematics and the development and testing of nuclear models as the most vital feature of the present program. Without the discipline of such a program, the explosion of information on nuclear structure will soon completely overwhelm the community of physicists who study the nuclear many-body problem. It is essential to recognize that the exploration of nuclear structure needs to be pursued on paths that have some promise of convergence.

Three areas of activity have been strongly pursued. First the groundwork has been laid for understanding shape coexistence in even-mass nuclei. Second, degrees of freedom that lie outside of the model space of the interacting boson model (IBM) have been investigated. Third, particle-core coupling is being looked at very critically.

A major breakthrough has come in understanding the factors that control the energies of pair excitations across closed shells. This is very simply described by a residual quadrupole-plus-monopole short range interaction between protons and neutrons acting primarily on correlated pairs of protons and correlated pairs of neutrons. This now paves the way to a quantitative theory of shape coexistence in nuclei, both even and odd mass. This work is being done in collaboration with K. Heyde and P. van Isacker (Institute of Nuclear Physics, Gent, Belgium) for which a NATO travel grant has been awarded to the author and K. Heyde.

The first part of the program to study shape coexistence in nuclei is completed. The reviews of coexistence in odd-mass nuclei (in collaboration with K. Heyde and coworkers (Gent) and R. A. Meyer (LLNL)) has been published in Physics Reports. A "spin-off" of this -- the interaction between intruder states and octupole states in N = 83 nuclei was published in Physics Letters B. Data on coexistence in even-mass nuclei have been summarized in papers that have been published in Proc. of the Workshop on Bosons in Nuclei, Drexel University (nuclei near closed shells), Nuclear Physics A (deformed nuclei), Proc. of the International Symposium on In-Beam Nuclear Spectroscopy, Debrecen (nuclei near subshell gaps) and Nuclear Physics A (detailed IBM calculation for $^{114}$Cd). The picture that has emerged supports a new class of nuclear structure which is associated with intruder states and shape coexistence and occurs at low energy near a closed shell when the number of active nucleons of the other type is maximal. This has its most dramatic manifestation near Z = 82, N = 104 where much of the UNISOR work is concentrated. In fact this picture has been the product of endeavoring to understand the UNISOR data on neutron-deficient Pt, Au, Hg and Tl nuclei. As a corollary to this, these new structures even become the ground states in the Pt, Au and Hg isotopes near N = 104, thus playing a role in the determination of nuclear stability and ground state properties. The influence of this on nuclear masses was discussed in a paper which will be published in Proc. of the 7th International Conference on Atomic Masses and Fundamental Constants, Darmstadt-Seeheim. Currently, the program is being continued with detailed calculations (using the IBM and modified by Duval and Barrett--Phys. Lett. 100B, 223 (1981)) for the even-Pt isotopes and a study of E0 transition systematics to ascertain if these transitions can be used as a tool to identify coexisting bands in nuclei. The Pt calculations are being done in collaboration with B. E. Gnade (Texas Instruments Corp., Dallas, Tx.).

The IBM has been a development of major significance for nuclear structure. It continues to accomodate the vast array of phenomena being observed. Continuing on from a thorough-going assessment of experimental tests of the IBM in its simplest forms (which was published last year) this program has addressed the experimental evidence for degrees of freedom that lie outside of the IBM model space. The occurrence of shape coexistence and intruder states at low energy, as described above, is the single most important feature of nuclear structure that lies outside of the basic IBM model space. In addition, attention has been given to collective octupole and hexadecopole degrees of freedom and their description in terms of f bosons and g bosons, respectively. A systematic calculation of octupole states in the rare earth region within an IBM description is in progress. This is being done in collaboration with B. R. Barrett and A. Barfield (Univ. of Arizona, Tucson), and constitutes part of the Ph.D. thesis work of A. Barfield. The present status of empirical evidence for degrees of freedom outside of the IBM model space has been summarized in papers that have been published in Proc. of the Workshop on Bosons in Nuclei, Drexel University, Proc. of the International Symposium on In-Beam Nuclear Spectroscopy, Debrecen and Nuclear Physics A and invited talks given at the 187th ACS National Meeting, St. Louis and the International Workshop on Interacting Boson-Boson and Boson-Fermion Systems, Gull Lake. The topics of broken-pair states and incoherent pairing correlations (the "non-collective" states) are now being addressed. These are relevant to the study of $^{120}$Sn at TRISTAN. Progress has been made in the systematic identification of these degrees of freedom in the even-Sn, -Cd and -Te isotopes.

Considerable progress has been made in the study of particle-core coupling. This is considered to provide a vital and little used insight into core structure, especially IBM parameterizations of doubly-even nuclei. We have adopted the Dönau-Frauendorf presctiption (F. Dönau and S. Frauendorf, Phys. Lett. 71B, 263 (1977)) for particle-core coupling. This prescription can accept core matrix elements from any suitable source (e.g., IBM, rigid rotor, triaxial rotor, experiment) and calculate the spectrum of an odd-mass nucleus. Calculations using the IBM Hg cores of Barfield, et al., (Z. Phys. A311, 205 (1983)) and the coupling of proton $h_{9/2}$ particles, proton $h_{11/2}$ holes and neutron $i_{13/2}$ quasiparticles compared to experimental (UNISOR) data on the odd-mass Tl, Au and Hg isotopes, respectively, reveals serious inadequacies in the IBM core description. These core descriptions were based on global fits of parameters to excitation energies, B(E2) values and quadrupole moment data in even-mass Hg, Pt, Os and W isotopes and specific fine tuning to the excitation energies of the even-mass Hg isotopes. The odd-particle "sees" these cores in the particle-core coupling manifested in the neighboring odd-mass nuclei. This result suggests that odd-A spectra are a vital input in determining even-mass core parameters in the IBM. Some preliminary results of this program have been presented in a paper to appear in Proc. of the International Workshop on Interacting Boson-Boson and Boson-Fermion Systems, Gull Lake. This work is being done in collaboration with P. Semmes (School of Chemistry, Georgia Tech) and G. Leander (UNISOR). This will constitute part of the Ph.D. thesis work of Mr. P. Semmes.

The pursuit of nuclear systematics and models, as it relates to degrees of freedom outside of the IBM model space and shape coexistence, brings three areas of the above experimental program into focus: (i) the near degenerate coexisting shapes in the neutron-deficient Pt, Au, Hg and Tl region, (ii) the existence of well-defined coexisting collective bands in the even-mass Sn isotopes, (iii) the observation of all degrees of freedom below 3 MeV in the even-Sn isotopes. The first topic continues to be a major area of study because of its uniqueness. The second and third topics are accessible at TRISTAN. In particular, the study of levels in $^{120}Sn$ will provide vital information relating to topics (ii) and (iii). The role of systematics and detailed nuclear spectroscopy far from $\beta$ stability was the subject of an invited paper to appear in Proc. of the TRIUMF-ISOL Workshop, Mr. Gabriel and an invited paper which will appear in Proc. of the International Symposium on Nuclear Orientation and Nuclei Far From Stability, Leuven. The work on the papers describing the systematic features of the odd-mass Au and Hg isotopes has been temporarily halted due to the heavy work load (as already noted earlier) and to the developments regarding particle-core coupling in these isotopes.

## 4.0 Personnel

Senior Staff:

Dr. J. L. Wood, Senior Research Scientist, Principal Investigator (Full time, Feb. 1 - Aug. 25, Sept. 9 - Oct. 31 (8 1/2 months); Half time, Nov. 1 - Jan. 31 (3 months)).

Graduate Students:

Mr. Chris Papanicolopulos, Ph.D. thesis work (Half time research assistant, Feb. 1 - Sept. 15 (7 1/2 months)).

Mr. Paul Semmes (School of Chemistry, Georgia Tech), Ph.D. thesis work (Half time research assistant, Sept. 16 - Jan 31 (4 1/2 months)).

## 5.0 Summary of Publications and Preprints, Abstracts and Presentations at Conferences, 1984

1. "Decay of Mass Separated $^{187}$Au (8.4 min) to $^{187}$Pt," B. E. Gnade, R. W. Fink and J. L. Wood, Nucl. Phys. A406, 29 (1983).

2. "The Level Scheme of $^{114}$Cd from (n,$\gamma$) and (d,p) Studies," A. Mheemeed, K. Schreckenbach, G. Barreau, H. R. Faust, H. G. Börner, R. Brissot, P. Hungerford, H. H. Schmidt, H. J. Scheerer, T. von Egidy, K. Heyde, J. L. Wood, P. van Isacker, M. Waroquier, G. Wenes, M. Stelts and J. Valentin, Nucl. Phys. A412, 113 (1984).

3. "Coexistence in Odd-Mass Nuclei," K. Heyde, P. van Isacker, M. Waroquier, J. L. Wood and R. A. Meyer, Phys. Repts. 102, 291 (1983).

4. "Experimental Evidence for the Need to Extend the IBA Beyond N, s and d: Deformed Nuclei," J. L. Wood, Nucl. Phys. A421, 43c (1984).

5. "Phenomenological Aspects of the IBM," J. L. Wood in Proc. of the Workshop on Bosons in Nuclei, Drexel University, Philadelphia, USA, 28-29 January 1983, ed. D. H. Feng, S. Pittel and M. Vallieres (World Scientific Publ. Co., Singapore, 1984), p. 19.

6. "Interaction Between Neutron Particle-Hole and Octupole Core-Coupled States in N = 83 Nuclei," R. A. Meyer, K. Heyde, P. van Isacker, M. Waroquier, J. Moreau and J. L. Wood, Phys. Lett. 140B, 159 (1984).

7. "The Decay of $^{188}$Tl and Observed Shape Coexistence in the Bands of $^{188}$Hg," J. D. Cole, J. H. Hamilton, A. V. Ramayya, W. Lourens, B. van Nooijen, H. Kawakami, L. A. Mink, E. H. Spejewski, H. K. Carter, R. L. Mlekodaj, G. A. Leander, L. L. Riedinger, C. R. Bingham, E. F. Zganjar, J. L. Wood, R. W. Fink, K. S. Toth, B. D. Kern and K. S. R. Sastry, Phys. Rev. C (in press).

8. "Subshell Gaps at N = 40 and Z = 40 and Shape Coexistence in the fpg Shell," J. L. Wood, in Proc. of the International Symposium on In-Beam

Nuclear Spectroscopy, Debrecen, Hungary, May 14-18, 1984, ed. T. Fenyes, *et al*., to be published.

9. "Particle-Core Coupling Calculations for the Positive Parity States in the Odd-Mass Hg Isotopes as a Test of IBM Core Descriptions," P. B. Semmes, G. A. Leander and J. L. Wood, in Proc. of the International Workshop on Interacting Boson-Boson and Boson-Fermion Systems, Gull Lake, Michigan, USA, May 28-30, 1984, ed. O. Scholten (to be published).

10. "Recent Results at UNISOR: Ideas for Future Studies at ISOL Systems," J. L. Wood, in Proc. of the TRIUMF-ISOL Workshop, Mt. Gabriel, P. Quebec, Canada, June 13-16, 1984, ed. J. D'Auria (to be published).

11. "A Unified Description of Shape Coexistence in Nuclei: Implications for Ground State Properties," J. L. Wood, in Proc. 7th International Conference on Atomic Masses and Fundamental Constants, Darmstadt-Seeheim, West Germany, Sept. 3-7, 1984, ed. P. Armbruster and E. Roeckl (to be published).

12. "Valence Shells--How Strongly Do They Dominate the Low-Energy Structure of Nuclei?" J. L. Wood, invited talk, 187th ACS National Mtg., St. Louis, Missouri, April 8-13, 1984 [abstract].

13. "A New Class of Low-Energy Structure at Closed Shells: Levels in $^{187-191}$Tl," E. F. Zganjar, J. D. Cole and J. L. Wood, contribution, APS-DNP Mtg., Nashville, Tennessee, Oct. 18-20, 1984 [abstract: Bull. Am. Phys. Soc. 29, 1049 (1984)].

14. "Experimental Information on Degrees of Freedom Outside of the s,d Model Space," J. L. Wood, invited talk, International Workshop on Interacting Boson-Boson and Boson-Fermion Systems, Gull Lake, Michigan, USA, May 28-30, 1984.

15. "Nuclear Orientation as a Tool for Studying the Structure of Very

Unstable Nuclei," J. L. Wood, invited talk, International Symposium on Nuclear Orientation and Nuclei Far From Stability, Leuven, Belgium, Aug. 28-31, 1984.

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Annual Progress Report, September 30, 1985

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# NUCLEAR STRUCTURE FROM RADIOACTIVE DECAY

Annual Progress Report

U. S. Department of Energy

Contract DE-AS05-80ER10599

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## 1.0 Introductory Overview

The primary activity this year has been the continuing study of a quantitative description of intruder states and shape coexistence in nuclei. The focus has been on the Z = 82 region where it appears that the energies of intruder states scale as the number of correlated proton pairs. The theoretical part of this work is being done in collaboration with K. Heyde (Institute of Nuclear Physics, Gent, Belgium) for which a NATO travel grant has been awarded to the author and K. Heyde. Our first results appear in Phys. Lett. 155B, 303 (1985). The experimental part of this work is based on the UNISOR program and a collaboration with the Instituut voor Kern- en Stralingsfysika, Leuven, Belgium. Some of the Leuven work appears in the Phys. Rev. Lett. 54, 783 (1985) and Phys. Lett. 154B, 354 (1985).

Experiments at UNISOR have focused on the structure of the odd-mass Au isotopes. The nucleus $^{185}$Au has been carefully studied to resolve the disagreement over the nature of the very converted transitions in this region: A preliminary analysis of our results supports our earlier interpretation of such transitions in $^{187}$Au as E0+M1+E2 and contradicts the interpretation (C. Bourgeois et al., Nucl. Phys. A386, 308 (1982)) of such transitions in $^{185}$Au as anomalous M1's. This will clear the way to completing our study of shape coexistence in the neutron-deficient Au isotopes. This work constitutes part of the Ph.D. thesis work of Mr. C. Papanicolopulos. Some preliminary details are reported in Bull. Am. Phys. Soc. 30, 1275, DC11 (1985).

On a broader scale, the UNISOR work continues to center on the new class of nuclear structure which is associated with intruder states and shape coexistence and occurs at low energy near a closed shell when the number of active nucleons of the other type is maximal (i.e., mid shell). In the Z = 82 region the identification of all intruder states at low energy requires a complete map of excited state systematics from the stability line (N $\sim$ 120) to far-from-stability regions (N $\sim$ 104). To continue this program, a number of key studies are in progress or are planned. Data analysis is in progress or temporarily on "hold" for $^{187,191}$Au and $^{189,191,193}$Tl. At the time of writing, running time is approved to study $^{189}$Au. Proposals to study $^{195}$Tl and to further study $^{191}$Au have been submitted. A vital constituent of a "complete map" of excited state systematics is unique spin-parity assignments to all low-lying states. To further this, laser spectroscopy is being used to determine spins and magnetic moments (as well as isotope and isomer shifts and quadrupole moments) of ground states and metastable states. A collaboration with the laser spectroscopy group at ISOLDE (CERN, Geneva) has been formed to study neutron-deficient Au isotopes. Running time is scheduled for December 1985. A proposal to study the neutron-deficient Pb isotopes at UNISOR using laser spectroscopy has been submitted. This will constitute part of the Ph.D. thesis work of Mr. J. C. Griffin (Georgia Tech, School of Chemistry/ORAU Fellow). (These studies will be followed with nuclear orientation studies at UNISOR to uniquely determine the spins of the excited states.)

A number of theoretical collaborations, in addition to the shape coexistence and intruder state work, are in progress. An interacting boson description (including shape coexistence) of the even-Pt isotopes is in progress in collaboration with Dr. B. E. Gnade (Texas Instruments, Dallas). A study of particle-core coupling is being made, using the Dönau-Frauendorf model, to determine the sensitivity of the odd particle to the core parameters. This constituted part of the Ph.D. thesis of Dr. P. B. Semmes (Georgia Tech, School of Chemistry), and work is continuing with Dr. Semmes who is now at the Joint Institute for Heavy Ion Research, Oak Ridge. Finally, a description of negative parity collective states in even-mass rare earth nuclei is being studied using the interacting boson model with an $L^{\pi} = 3^-$ boson coupled to L = 0,2 bosons. This work is a collaboration with B. R. Barrett, University of Arizona, Tucson and constitutes part of the Ph.D. thesis work of one of his students, Ms. A. F. Barfield. Some preliminary details are reported in Bull. Am. Phys. Soc. 30, 1276, DD6 (1985).

Other activities have included the election of the author to the chairmanship of the Executive Committee of the Holifield Heavy-Ion Research Facility (HHIRF) Users Group; seminars and colloquia at the University of Jyväskylä (Finland) and Notre Dame University; and an invited talk at the 7th Europhysics Study Conference: Synthesis and Structure of Exotic Nuclei and Atoms (in Varna, Bulgaria). At the time of writing, the author plans to be a Visiting Professor at the Katholieke Universiteit, Leuven (Belgium) during the period November 1985 - January 1986. This will permit continuation of the collaborations with the groups at the Institute for Nuclear Physics in Gent and the Instituut voor Kern- en Stralingsfysika in Leuven. Colloquia are planned at the Kernfysisch Versneller Instituut, Groningen (The Netherlands), the University of Göttingen (West Germany) and CERN, Geneva (Switzerland) during this period.

## 2.0 Experimental Program

A major area of activity is the study of neutron-deficient nuclei around the Z = 82 shell closure, with special emphasis on the levels of the odd-mass Pt, Au, Hg, Tl, Pb and Bi isotopes. A crucial ingredient of this work is the systematic investigation of low-energy structural features of sequences of isotopes (and isotones) over many adjacent mass numbers. This has a two-fold purpose. First, it enables us to build up a very complete picture of the nuclear structure that connects the regions of stable nuclei (where, e.g., transfer reactions and Coulomb excitation permit the measurement of detailed spectroscopic properties) with regions far from stability, where detailed spectroscopic information is very limited. Second, it provides a map of the excitation degrees of freedom as a function of the changing proton and neutron number over broad mass regions. The mass region under study possesses the richest variety of nuclear excitations observed anywhere on the mass surface. It is intersected by the Z = 82 shell closure, and bounded by the strongly deformed nuclei with $Z \leq 76$ and the N = 126 shell closure. Between Z = 76 and Z = 82 there is a shape transition from strongly deformed prolate axial symmetry through oblate axial asymmetry to spherical symmetry. This transition has alternatively been described in terms of the interacting boson approximation (IBA) as a transition from the SU(3) through the O(6) limiting algebraic symmetries of the IBA Hamiltonian. Finally, and most dramatically of all, an island of ground-state deformation has been established adjacent to the Z = 82 closed shell for the very neutron-deficient isotopes of Hg and Pt. This deformation is now understood in terms of proton intruder orbitals which give rise to the large deformation ($\beta \sim 0.27$) through an increased proton valence space and the proton-neutron residual interaction. Unless otherwise indicated, the experiments described involve UNISOR.

2.1 Very Neutron-Deficient Au Decays

An attempt to study the very neutron-deficient Pt isotopes (A = 176 - 181) via the corresponding Au decays was not successful. However, the experiment revealed that in the Sm + Cl bombardments, the beam of Cl ions gave much less heating of the target and catcher than, e.g., a $^{16}O$ beam. This resulted in negligible release of Au activity into the ion source. A heated target/catcher design is being investigated. This work is in collaboration with E. F. Zganjar (LSU) and C. R. Bingham (U. Tenn.).

2.2 Odd-Mass Hg Decays

As mentioned earlier, a careful study of the $^{185m,g}Hg \rightarrow {}^{185}Au$ decay schemes has been made. Detailed $\gamma$-$\gamma$ and e-$\gamma$ coincidence measurements reveal serious errors in the decay schemes reported by C. Bourgeois et al., Nucl. Phys. A386, 308 (1982). In particular, a number of very converted transitions (i.e., $\alpha_K >> \alpha_K(M1)$) were clearly located incorrectly in the $^{185}Au$ decay scheme by these authors. These transitions appear in the spectrum as closely spaced doublets or multiplets which can only be decomposed unambiguously using coincidence data.

In the work of Bourgeois et al., the $\gamma$-$\gamma$ measurements were insufficient to decompose these multiplets and no e-$\gamma$ measurements were made. Consequently, we disagree with the earlier interpretation of the very converted transitions as anomalously converted M1 transitions (due to large "penetration" effects). Our $^{185}Au$ decay scheme is consistent with the interpretation of these transitions as E0+M1+E2. This concurs with our decay scheme for $^{187}Au$. A number of new structural features are seen at low energy in $^{185}Au$ in our work which suggest, from systematics, additional low-energy states will be found in $^{187}Au$. We are looking for evidence of these states in our $^{187m,g}Hg \rightarrow {}^{187}Au$ data. This work is being done in close collaboration with an in-beam $\gamma$-ray study of high-spin states in $^{185}Au$ by the Univ. of Tenn. group. The work is a collaboration with E. F. Zganjar (LSU) and L. L. Riedinger and A. J. Larabee (Univ. Tenn.) and constitutes part of the Ph.D. thesis work of Mr. C. Papanicolopulos (Georgia Tech, School of Physics). Some preliminary details are reported in the Bulletin of the American Physical Society.

Beam time is approved to study the $^{189m,g}Hg \rightarrow {}^{189}Au$ decay schemes. Very little is known about low-spin excited states in $^{189}Au$. These will be selectively populated in the $^{189g}Hg$ ($J = 3/2^-$) decay. Further, nothing is known about very converted transitions in these decays. These studies will provide a clearer systematics picture for $^{185,187}Au$ and for $^{191}Au$ (see below). This is a collaboration with E. F. Zganjar (LSU).

A $\gamma$-$\gamma$ coincidence study of the $^{191m,g}Hg \rightarrow {}^{191}Au$ has been completed and is almost completely analyzed. This forms the starting point of an investigation of excited states in $^{191}Au$. Knowledge of these is needed for understanding the systematics of the odd-Au isotopes and to explore the possibility that a dynamical spinor symmetry underlies the structure of $^{191}Au$, similar to that suggested in $^{193}Au$ (J. L. Wood, Phys. Rev. C24, 1788 (1981)). (The $^{189}Au$ study - see above - will extend this study of dynamical spinor symmetry.) A proposal has been submitted to obtain e-$\gamma$ coincidence data for $^{191}Au$ to search for very converted transitions in this nucleus. The nuclear orientation data, for the $^{191m}Hg \rightarrow {}^{191}Au$ decay, obtained at the KOOL facility (Leuven, Belgium), has been analyzed. Evidently, there were computer problems! This measurement will be repeated and a study of $^{191g}Hg \rightarrow {}^{191}Au$ made when the UNISOR low-temperature nuclear orientation facility becomes operational. This work is in collaboration with E. F. Zganjar (LSU) and K. S. Krane (Oregon State Univ., Corvallis).

## 2.3 Neutron-Deficient Tl Decays

The study of the $^{188}Tl \rightarrow {}^{188}Hg$ decay scheme has been published in Physical Review C.

The elucidation of the $^{189m}Tl \rightarrow {}^{189}Hg$ and $^{191m}Tl \rightarrow {}^{191}Hg$ decay schemes has been restarted. This work is in collaboration with E. F. Zganjar (LSU) and B. E. Gnade (Texas Instruments Corp., Dallas). These decays will be the focus of low-temperature nuclear orientation studies as soon as the UNISOR refrigerator becomes operational. The analysis of the $^{187m,g}Tl \rightarrow {}^{187}Hg$ decay schemes remain temporarily halted due to limited manpower.

## 2.4 Odd-Mass Pb Decays

The elucidation of the $^{189m,191m,193m}Pb \rightarrow Tl$ decay schemes has been temporarily halted. The Pb parents have J = $13/2^{+}$ and thus only populate high-spin states in the Tl daughter nuclei. To advance the study of the neutron-deficient odd-mass Tl isotopes, low-spin information is needed together with a detailed "bridging" study of high- and low-spin states in $^{195}Tl$ which will connect with the systematics of the heavier odd-mass Tl isotopes. A proposal has been submitted to study the decays of $^{195m,g}Pb \rightarrow {}^{195}Tl$. To produce $^{195g}Pb$, it will be necessary to "enter" the mass chain at $^{195}Bi$, since direct heavy-ion production of $^{195}Pb$ yields only $^{195m}Pb$. (A similar approach will be used to study low-spin states in the lighter odd-mass Tl isotopes.) This work is in collaboration with E. F. Zganjar (LSU) and C. R. Bingham (U. Tenn.)

## 2.5 Neutron-Deficient Bi Decays

The $\alpha$-decay of very neutron-deficient Bi isotopes has been studied at the Leuven Isotope Separator On-Line (LISOL) facility in Louvain-la-Neuve, Belgium. Preliminary results have been published in Physical Review Letters and a written contribution has been made to the Chicago ACS Meeting. The decay of the odd-mass Bi ground states and isomeric states provide a strong spectroscopic confirmation of intruder states in the Bi and Tl isotopes through their reduced α widths. The measurements also yielded excitation energies of these intruder states: this is discussed furhter in Section 3.0 below.

An attempt to study the very neutron-deficient Pb isotopes ($^{190,192}$Pb) (at UNISOR) via the corresponding Bi decays was not successful. As noted in Section 2.1 above, beam heating from the Cl ions in the Dy + Cl bombardments did not provide a vital source of target/catcher heating. This will be corrected. This work is in collaboration with E. F. Zganjar (LSU).

2.6 Neutron-Deficient Po Decays

The α decay of $^{194,196}$Po to $^{190,192}$Pb has been studied at LISOL. Results have been published in Physics Letters B. These α decays populate the low-lying excited $0^+$ states in the Pb isotopes: thus providing the first identification of the very low (intruder) $0^+$ state in $^{190}$Pb (at 669 keV). These intruder states are discussed further in Section 3.0 below.

The study of the $^{201m,g}$Po $\rightarrow$ $^{201}$Bi decay schemes is being prepared for publication. This work (done at UNISOR) is in collaboration with R. A. Braga (Georgia Tech, School of Chemistry).

2.7 Neutron-Deficient At Decays

The α decay of $^{197}$At to $^{193}$Bi has been studied at LISOL. Preliminary results appear in a written contribution to the Chicago ACS Meeting. Unhindered α decay of $^{197m}$At to the intruder state in $^{193}$Bi identifies $^{197m}$At as an intruder state at the very low excitation energy of 52 keV.

2.8 Other Decay Scheme Studies

Decay scheme studies at TRISTAN ($^{120}$In $\rightarrow$ $^{120}$Sn) have been terminated in view of the planned shutdown of this facility. As noted above the main thesis work of Mr. C. Papanicolopulos has been shifted to a study of $^{185}Au$ (from $^{120}Sn$).

3.0 Nuclear Systematics and Models

The development of nuclear systematics and models for a better understanding of nuclear structure continues to be a major activity on this contract. Three areas have been pursued in the past year: intruder states and shape coexistence; a description of collective negative parity states in the rare earth region in terms of the interacting boson model; and an exploration of particle-core coupling to ascertain the sensitivity of an unpaired nucleon as a probe of core collectivity.

By far the most extensive activity has been the investigation of shape coexistence and intruder states. Systematics strongly support an intimate connection between the two. Further, intruder state energies strongly correlate with the number of active (valence) proton pairs and neutron pairs suggesting that the key to understanding these states lies in understanding the residual proton-neutron force. A model based on a proton-neutron force with monopole and quadrupole components is being developed. Preliminary results have been published in Physics Letters B. A written contribution was also made to the Chicago ACS Meeting. Current investigations include: an analysis of band mixing to obtain empirical mixing matrix elements between intruder and "normal" states; a study of Coulomb matrix elements for proton intruder states; and continued studies of models with proton-neutron forces. This work is in collaboration with K. Heyde (Gent, Belgium).

The develoment of models to describe shape coexistence and intruder states is being done with a careful view to experimental data. Coexistence in $^{145}$Gd has been identified, based on experiments done by the University of Cologne (West Germany) nuclear physics group. A paper has been written in collaboration with the author and K. Heyde (Gent) and submitted to Nuclear Physics A. Coexistence in $^{184}$Pt has been confirmed by B(E2) measurements done by a University of Notre Dame/Argonne National Laboratory collaboration. Preliminary results appear in a contribution to the Chicago ACS Meeting written in collaboration with the author. The measurement of intruder state energies in the Tl, Pb and Bi isotopes (work done at LISOl, see Sections 2.5 and 2.6) provides evidence that there is a simple scaling of these energies proportional to the number of active proton pairs. Preliminary results appear in a contribution to the Chicago ACS Meeting in collaboration with the Leuven group. The interacting boson model with band mixing, of Duval and Barrett (Phys. Lett. 100B, 223 (1981)), is being applied to the neutron-deficient Pt isotopes. This is being done in collaboration with B. E. Gnade (Texas Instruments, Dallas) and takes advantage of exclusive access to a VAX 11-750 with 8 Mbyte core and 1 Gbyte disk (although the model is simple, the large number of bosons involved in the model space requires considerable computing power).

Particle-core coupling is being explored to better understand the sensitivity of an unpaired nucleon to core collectivity. This is being done using the Dönau-Frauendorf model (Phys. Lett. 71B, 263 (1977)). This is a collaboration with Dr. P. B. Semmes (Georgia Tech, School of Chemistry; now at the Joint Institute for Heavy-Ion Research, Oak Ridge): this work constituted part of his Ph.D. thesis. Some results have been published in the Proceedings of the Workshop on Interacting Boson-Boson and Boson-Fermion Systems. This development will be used to constrain core descriptions in the neutron-deficient Pt isotopes (see above) by simultaneously fitting neighboring odd-mass spectra.

The description of negative parity collective states in even-mass rare earth nuclei is being studied using the interacting boson model with an $L^{\pi}$ = $3^{-}$ boson (f boson) coupled to L = 0,2 (s,d) bosons. This work is in collaboraton with B. R. Barrett, University of Arizona, Tucson and constitutes part of the Ph.D. thesis work of one of his students, Ms. A. F. Barfield. Some preliminary details are reported in the Bulletin of the American Physical Society.

## 4.0 Personnel

### Senior Staff

Dr. J. L. Wood, Senior Research Scientist (Feb. 1 - Aug. 31), Associate Professor (Sept. 1 - Jan 31), Principal Investigator. Full time 6 months, half time 2 1/2 months.

### Graduate Students

Mr. Chris Papanicolopulos, Ph.D. thesis work. Half time 6 months.

Mr. Paul Semmes (School of Chemistry, Georgia Tech), Ph.D. thesis work. Half time 6 months.

## 5.0 Summary of Publications and Preprints, Abstracts and Presentations at Conferences, 1985


1. "The Decay of $^{188}$Tl and Observed Shape Coexistence in the Bands of $^{188}$Hg," J. D. Cole, J. H. Hamilton, A. V. Ramayya, W. Lourens, B. van Nooijen, H. Kawakami, L. A. Mink, E. H. Spejewski, H. K. Carter, R. L. Mlekodaj, G. A. Leander, L. L. Riedinger, C. R. Bingham, E. F. Zganjar, J. L. Wood, R. W. Fink, K. S. Toth, B. D. Kern and K. S. R. Sastry. Phys. Rev. C30, 1267 (1984).
2. "Subshell Gaps at N = 40 and Z = 40 and Shape Coexistence in the fpg Shell," J. L. Wood, in Proc. of the International Symposium on In-Beam Nuclear Spectroscopy, Debrecen, Hungary, May 14-18, 1984, ed. Zs. Dombradi and T. Fenyes (Akademiai Kiado, Budapest, 1984), p. 31.
3. "Particle-Core Coupling Calculations for the Positive Parity States in the Odd-Mass Hg Isotopes as a Test of IBM Core Descriptions," P. B. Semmes, G. A. Leander and J. L. Wood, in Interacting Boson-Boson and Boson-Fermion Systems, ed. O. Scholten (World Scientific Publ. Co., Singapore, 1984), p. 208.
4. "Recent Results at UNISOR: Ideas for Future Studies at ISOL Systems," J. L. Wood, in Proc. of the TRIUMF-ISOL Workshop, Mont Gabriel, Quebec, 13-16 June 1984, eds. J. Crawford and J. M. D'Auria, TRI-84-1, p. 87.
5. "A Unified Description of Shape Coexistence in Nuclei: Implications for Ground State Properties," J. L. Wood, in Proc. of the 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, West Germany, 3-7 September, 1984, ed. O. Klepper, (Technische Hochschule Darmstadt Lehrdruckeren, Darmstadt, West Germany, 1984), p. 516.
6. "Nuclear Orientation as a Tool for Studying the Structure of Very

Unstable Nuclei," J. L. Wood, Hyperfine Interactions 22, 379 (1985).

7. "A Shell-Model Interpretation of Intruder States and the Onset of Deformation in Even-Even Nuclei," K. Heyde, P. Van Isacker, R. F. Casten and J. L. Wood, Phys. Lett. 155B, 303 (1985).

8. "α Decay of Neutron-Deficient Odd Bi Nuclei: Shell-Model Intruder States in Tl and Bi Isotopes," E. Coenen, K. Deneffe, M. Huyse, P. van Duppen and J. L. Wood, Phys. Rev. Lett. 54, 1783 (1985).

9. "Low-Lying $J = 0^+$ States in $^{190,192}$Pb Populated in the α Decay of $^{194,196}$Po," P. van Duppen, E. Coenen, K. Deneffe, M. Huyse and J. L. Wood, Phys. Lett. 154B, 354 (1985).

10. "Two-Hole One-Particle Excitations in the Odd-Mass N = 81 Nucleus $^{145}$Gd," K. O. Zell, P. von Brentano, D. Bazzacco, J. L. Wood and K. Heyde, submitted to Nucl. Phys. A.

11. "Intruder States in Highly Neutron-Deficient Pt Nuclei: Evidence from Lifetime Measurements?" U. Garg, M. W. Drigert, A. Chandhury, E. G. Funk, J. W. Mihelich, D. C. Radforrd, H. Helppi, R. Holzman, R. V. F. Janssens, T. L. Khoo, A. M. Van den Berg and J. L. Wood, to be published in Proc. of the ACS Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago 1985, ed. D. S. Brenner and R. A. Meyer.

12. "Study of Intruder States in the Z = 82 Region by the $\beta^+$/EC and α Decay of Neutron-Deficient Bi, Po and At Nuclei," M. Huyse, E. Coenen, K. Deneffe, P. van Duppen and J. L. Wood, ibid.

13. "Towards a Shell-Model Description of Intruder States and the Onset of Deformation," K. Heyde, P. Van Isacker, R. F. Casten and J. L. Wood, ibid.

14. "Towards a Shell-Model Description of Intruder States and the Onset of Deformation," K. Heyde, P. Van Isacker, R. F. Casten and J. L. Wood, invited paper, ACS Mtg., Chicago, Illinois, Sept. 8-13, 1985 [abstract].

15. "Study of Intruder States in the Z = 82 Region by the $\beta^+$/EC and $\alpha$ Decay of Neutron Deficient Bi, Po and At Nuclei," M. Huyse, E. Coenen, K. Deneffe, P. Van Duppen and J. L. Wood, invited paper, ACS Mtg., Chicago, Illinois, Sept. 8-13, 1985 [abstract].

16. "Coexisting Collective Structure in $^{185}$Au," E. F. Zganjar, C. D. Papanicolopulos, J. L. Wood, R. A. Braga, R. W. Fink, A. J. Larabee, M. Carpenter, D. Love, C. R. Bingham, L. L. Riedinger and J. C. Waddington, Bull. Am. Phys. Soc. 30, 1275, DC11 (1985) [abstract].

17. "An Interacting Boson Model Description of Octupole Bands in Deformed Nuclei," A. F. Barfield, B. R. Barrett, O. Scholten and J. L. Wood, Bull. Am. Phys. Soc. 30, 1276, DD6 (1985) [abstract].

18. "Intruder States in Heavy Nuclei," J. L. Wood, invited talk, 7th Europhysics Study Conference: Synthesis and Structure of Exotic Nuclei and Atoms, 15-17 Sept. 1985, Varna (Bulgaria).

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Contract DE-AS05-80ER10599


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August 31, 1986


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## 1.0 Introductory Overview

The primary focus this year has been studies of intruder states and shape coexistence in the neutron-deficient Z $\sim$ 82 region. Most notably, the structure of the neutron-deficient Au isotopes has been studied by on-line decay scheme spectroscopy of mass-separated isotopes at UNISOR (in a collaboration with LSU), by on-line low-temperature nuclear orientation of mass-separated isotopes at LISOL (in a collaboration with the Institut voor Kern- en Stralingsfysika, Leuven, Belgium), and by on-line laser atomic hyperfine spectroscopy of mass-separated isotopes at ISOLDE (in collaboration with the Universität Mainz, Fed. Rep., Germany). Theoretical studies of the neutron-deficient Au isotopes have been made in collaboration with Dr. P. Semmes (Joint Institute for Heavy Ion Research, Oak Ridge). The most dramatic result is the observation of a sudden large increase in the mean-square charge radius between $^{187}$Au and $^{186}$Au, seen in the laser spectroscopy measurements at ISOLDE. The anomalously large mean-square charge radius seen in $^{186}$Au persists in $^{185}$Au where detailed information on excited states has been obtained (at UNISOR), together with a value for the ground-state magnetic moment (measured at LISOL).

These studies are part of a larger program directed towards building a complete picture of shape coexistence in the neutron-deficient Z $\sim$ 82 region. Early ideas (see e.g., Physics Reports 102, 291 (1983); Phys. Letts. 155B, 303 (1985)) emerging from work on this contract have been based on limmited data. The models developed need to be tested in detail over a much more extensive range of mass numbers. The Z $\sim$ 82 region is especially attractive for the study of shape coexistence, in this respect, because the coexisting shapes are nearly degenerate in energy over the widest spread of mass numbers anywhere on the mass surface.

Because this region of shape coexistence is very far from beta stability, special techniques have had to be developed to provide adequate spectroscopic information on the nuclei involved. A key tool, in this respect, is systematics. This requires complete information on excited states (up to some specified energy and spin). This part of the program has continued at UNISOR with very detailed studies of the excited states of $^{189}Au$, $^{191}Au$, $^{189}Hg$, $^{191}Hg$ and $^{195}Tl$, from radioactive decay of the corresponding Hg, Tl and Pb isotopes (in collaboration with LSU and Univ. Tenn.). Gamma-ray and conversion-electron data have been obtained and are being analyzed. Low-temperature nuclear orientation will be performed at UNISOR in the near future to obtain unique spin assignments and transition multipolarities (see the accompanying Renewal Proposal). These isotopes serve as "benchmarks" in the regions between the beta stability line and the far from stability regions of primary interest.

The data obtained so far are consistent with the mechanism of shape coexistence being due to promotion of protons across the Z = 82 shell gap, so as to increase the number of active or valence proton pairs. In doubly-even nuclei this can be achieved by promoting two protons across the shell gap. In odd-proton nuclei it can be achieved by promoting a single proton across the gap, creating an extra hole pair for $Z < 82$ and an extra particle pair for $Z > 82$. However, it is possible for both mechanisms to happen simultaneously, i.e., the promotion of three protons across the Z = 82 shell gap. Evidence has been obtained from work at UNISOR that this is occurring in $^{185}Au$ and $^{187}Au$. It raises the intriguing question of whether or not four different coexisting shapes occur in $^{185,187}Au$. The $^{185}Au$ study constitutes part of the doctoral thesis work of Mr. C. D. Papanicolopulos (School of Physics, Ga. Tech). This picture is being pursued theoretically using the prescription of

Duval and Barrett applied to the proton-neutron interacting boson model and the Dönau-Frauendorf description of particle-core coupling (in collaboration with P. Semmes and Dr. B. E. Gnade, Texas Instruments Corp., Dallas). If both mechanisms occur together, the Fermi energy for the unpaired proton will shift; this should be reflected in the proton single-particle and single-hole spectra observed, and will act as a signature to the structural mechanism. It is too early to say whether or not the data on $^{185,187}Au$ support such a shift.

An important spectroscopic signature of shape coexistence appears to be the occurrence of strong E0 transitions, which can compete with E2 and/or M1 transitions. Thus, for example, six transitions with E0 components have been observed in the study of $^{185}Au$ at UNISOR. A thoroughgoing study of E0 transitions (and excited $0^+$ states in doubly-even nuclei) to better understand their use as a spectroscopic tool for identifying shape coexistence has been initiated. This is in collaboration with Prof. J. Kantele (University of Jyväskylä, Finland), Prof. K. Heyde (Institute for Nuclear Physics, Gent, Belgium), and Dr. R. A. Meyer (Lawrence Livermore Laboratory). A NATO travel grant has been awarded (commencement date Sept. 1, 1986) in support of this work.

One of the most distinctive systematic features of shape coexistence near to closed shells is the occurrence of an energy minimum near mid shell for the other type of nucleon, i.e., $N \sim 104$ for $Z \sim 82$ (see e.g., Physics Reports 102, 291 (1983)). This feature is being mapped "back towards stability" for $Z \sim 82$. Studies of excited states in $^{189}Au$ and $^{190}Hg$ at UNISOR are aimed at extending the systematic appearance of shape coexistence already established in $^{185,187}Au$ and $^{182,184,186,188}Hg$, respectively. Candidates for coexisting $0^+$ states in $^{192,194,196,198,200}Pb$ have also been established with a systematic increase in A: $192 \rightarrow 200$ in studies of the radioactive decay of the corresponding Bi isotopes at LISOL (in collaboration with the Instituut voor Kern- en Stralingsfysika, Leuven, Belgium).

Other experimental studies have included: laser atomic hyperfine spectroscopy of mass-separated lead isotopes at UNISOR (which constitutes part of the doctoral thesis work of Mr. J. Griffin, ORAU Fellow/School of Chemistry, Ga. Tech.); lifetime measurements of yrast states in $^{184}$Pt at ATLAS which establish a sudden increase in B(E2)'s, consistent with low-lying shape coexistence (in collaboration with Notre Dame and the ATLAS in-beam group at Argonne National Laboratory); and alpha decay of $^{197}$At at LISOL to identify the proton hole intruder state in $^{197}$At (in collaboration with IKS, Leuven).

Other theoretical studies have included: testing IBA core descriptions through particle-core coupling (in collaboration with P. Semmes, B. E. Gnade and the theory group of Prof. B. R. Barrett at the Univ. of Arizona, Tucson); further development in the description of intruder state energies, notably particle-hole interaction energies (in collaboration with the theory group of K. Heyde at the Institute for Nuclear Physics, Gent, Belgium); and the completion of investigations of degrees of freedom outside of the sd model space in the IBA with a study of octupole states in rare earth nuclei (in collaboration with B. R. Barrett, Univ. of Arizona, Tucson, and Dr. A. Barfield, Univ. of Arizona, for whom the work constituted part of her doctoral thesis.

Other activities have included the author serving as Chairman of the Executive Committee of the Holifield Heavy-Ion Research Facility (HHIRF) Users Group; serving as Chairman of the Organizing Committee for "The Workshop on Heavy Ion Physics and Instrumentation for a 15Tm Booster and Storage Ring" (at HHIRF), Oct. 2-4, Oak Ridge, Tenn.; and organizing a Symposium on "Nuclear Spectroscopic Quantities - Their Determination and Use" at the 192nd National

Meeting of the American Chemical Society, Sept. 8-9, Anaheim, Ca.

## 2.0 Experimental Program

A major area of activity is the study of neutron-deficient nuclei around the Z = 82 shell closure, with special emphasis on the levels of the odd-mass Pt, Au, Hg, Tl, Pb and Bi isotopes. A crucial ingredient of this work is the systematic investigation of low-energy structural features of sequences of isotopes (and isotones) over many adjacent mass numbers. This has a two-fold purpose. First, it enables us to build up a very complete picture of the nuclear structure that connects the regions of stable nuclei (where e.g., transfer reactions and Coulomb excitation permit the measurement of detailed spectroscopic properties) with regions far from stability, where detailed spectroscopic information is very limited. Second, it provides a map of the excitation degrees of freedom as a function of the changing proton and neutron number over broad mass regions. The mass region under study possesses the richest variety of nuclear excitations observed anywhere on the mass surface. It is intersected by the Z = 82 shell closure, and bounded by the strongly deformed nuclei with $Z \leq 76$ and the N = 126 shell closure. Between Z = 76 and Z = 82 there is a shape transition from strongly deformed prolate axial symmetry through oblate axial asymmetry to spherical symmetry. This transition has alternatively been described in terms of the interacting boson approximation (IBA) as a transition from the SU(3) through the O(6) limiting algebraic symmetries of the IBA Hamiltonian. Finally, and most dramatically of all, an island of ground-state deformation has been established adjacent to the Z = 82 closed shell for the very neutron-deficient isotopes of Hg and Pt. This deformation is now understood in terms of proton intruder orbitals which give rise to the large deformation ($\beta \sim 0.27$) through an increased proton valence space and the proton-neutron residual interaction. Unless otherwise indicated, the experiments described involve UNISOR.

## 2.1 Neutron-Deficient Au Isotopes

A major activity during the past year has been the analysis of the excellent γ-γ and e-γ coincidence data obtained for the $^{185m,g}Hg \rightarrow {}^{185}Au$ decay schemes measured in July 1985. As mentioned in last years' Annual Report, our $^{185}Au$ decay scheme is consistent with the very converted transitions observed having E0+M1+E2 multipolarity, in contradiction with the ISOCELE work (C. Bourgeois et al., Nucl. Phys. A386, 308 (1982)). The data support four distinct structures in $^{185}Au$: they can be classified as $^{184}Pt$ $(0_1^+; \pi 2p\text{-}6h) \otimes \pi^{+1}$; $^{184}Pt$ $(0_2^+; \pi 4h) \otimes \pi^{+1}$; $^{186}Hg$ $(0_1^+; \pi 2h) \otimes \pi^{-1}$; and $^{186}Hg$ $(0_2^+; \pi 2p\text{-}4h) \otimes \pi^{-1}$. The E0+M1+E2 transitions connect $^{184}Pt$ $(0_2^+) \otimes \pi^{+1} \rightarrow {}^{184}Pt$ $(0_1^+) \otimes \pi^{+1}$ states and $^{186}Hg$ $(0_2^+) \otimes \pi^{-1} \rightarrow {}^{186}Hg$ $(0_1^+) \otimes \pi^{-1}$ states. Further, there is evidence that the $^{186}Hg$ $(0_2^+) \otimes \pi^{-1}$ states have strongly-coupled bands built on them. Some preliminary results were reported at the Dubrovnik Conference in June 1986 and a paper was submitted for publication in the Proceedings. Short papers are in preparation describing these four structures in $^{185,187}Au$ and describing the systematic features of $^{185,187,189}Au$. The study of the $^{185m,g}Hg \rightarrow {}^{185}Au$ decay schemes constitutes part of the Ph.D. thesis of C. D. Papanicolopulos of the Ga. Tech School of Physics, and is a collaboration with Prof. E. F. Zganjar (LSU).

A γ-γ and e-γ coincidence study of the $^{189m,g}Hg \rightarrow {}^{189}Au$ decay schemes was made with very high statistics (72 million γ-γ events, 25 million e-γ events). These data are presently being analyzed. The $^{189}Au$ level scheme is being studied from the viewpoint of shape coexistence; as an example of dynamical spinor symmetry (of its low-lying positive parity states); and as a detailed benchmark nucleus in the Au systematics. Some preliminary results have been reported at the Washington Meeting of the American Physical Society in April 1986. On-line low-temperature nuclear orientation will be performed in the near future (see the accompanying Renewal Proposal) to establish unique spin assignments to levels and accurate transition multipolarities. (The latter are crucial to the separation of E2 and M1 components of $\Delta J = 0,1$ transitions in order to test E2 selection rules expected for a dynamical spinor symmetry (see e.g., J. L. Wood, Phys. Rev. C24, 1788 (1981)). This work is in collaboration with E. F. Zganjar (LSU).

As described in last year's Annual Report, a $\gamma$-$\gamma$ coincidence study of the $^{191m,g}Hg \rightarrow {}^{191}Au$ decay scheme has been completed and analyzed. Later this contract year it is expected that an e-$\gamma$ coincidence study will be made to locate very converted transitions. On-line low-temperature nuclear orientation will be performed in the near future (see the accompanying Renewal Proposal). This structure of $^{191}Au$ closely parallels $^{189}Au$ and is being studied for identical reasons (see above). This work is in collaboration with E. F. Zganjar and Prof. K. S. Krane (Oregon State Univ., Corvallis).

Low-temperature nuclear orientation was performed on $^{185,186}Au$ on-line at the LISOL/KOOL facility at the CYCLONE cyclotron in Louvain-la-Neuve, Belgium. Ground state magnetic moments were extracted and compared with various models. The experimental results are consistent with Nilsson model calculations corresponding to quadrupole deformations $\beta_2 \sim 0.25$. A paper has been submitted for publication. This work is in collaboration with the on-line low-temperature nuclear orientation group at Instituut voor Kern- en Stralingsfysika, Leuven, Belgium.

On-line laser atomic hyperfine spectroscopy was performed on $^{185,186,187,188,189m,189g}Au$ at the ISOLDE facility at CERN, Geneva, Switzerland. The results show a sudden large increase in the nuclear charge volume in going from $^{187}Au$ to $^{186}Au$. The large increase persists in $^{185}Au$. This is of comparable magnitude to the increase observed in going from $^{186}Hg$

to $^{185}$Hg. A paper has been prepared for publication and contributions to various meetings have been made describing different aspects of the measurements. This work is in collaboration with Prof. H.-J. Kluge and the laser atomic hyperfine spectroscopy group of the Universität Mainz, Fed. Rep. of Germany.

### 2.2 Neutron-Deficient Hg Isotopes

The elucidation of the $^{189m}$Tl $\rightarrow$ $^{189}$Hg and $^{191m}$Tl $\rightarrow$ $^{191}$Hg decay schemes continues. Some preliminary results for $^{189}$Hg will be reported at the Vancouver Meeting of the American Physical Society in October 1986. On-line low-temperature nuclear orientation will be performed in the near future on both these decays (see the accompanying Renewal Proposal). This work is in collaboration with B. E. Gnade and E. F. Zganjar.

The analysis of the $^{187m,g}$Tl $\rightarrow$ $^{187}$Hg decay schemes remain temporarily halted due to limited manpower. However, the data obtained so far are of limited quality and, thus, it is planned to study these decays with much higher statistics (see the accompanying Renewal Proposal).

The eventual goal of the odd-mass Hg studies is the establishment of spectroscopic information on shape coexistence in $^{185,187}$Hg. This is described in detail in the accompanying Renewal Proposal.

Later this contract year a study of the $^{190g}$Tl $\rightarrow$ $^{190}$Hg decay scheme is planned. The low-spin $^{190g}$Tl ($J^{\pi} = 2^{-}$) will be produced indirectly from $^{190}$Pb decay. The main interest in $^{190}$Hg is the location of the strongly deformed band seen in $^{182,184,186,188}$Hg. Systematics suggest that the band head should lie below 1.1 MeV. It will be sought by looking for the E0 and E0+M1+E2 transitions that characteristically de-excite these bands. This work is in collaboration with the UNISOR consortium.

## 2.3 Neutron-Deficient Tl Isotopes

As noted in last year's Annual Report, the elucidation of the $^{189m,191m,193m}Pb \rightarrow Tl$ decay schemes has been temporarily halted. This is due to lack of systematic information on low-spin states in the neutron-deficient Tl isotopes. This is because the Pb parents all have $J^{\pi} = 13/2^{+}$ and these only populate Tl high-spin states significantly. A $\gamma$-$\gamma$ and e-$\gamma$ coincidence study of the $^{195g}Pb \rightarrow {}^{195}Tl$ decay scheme has been made to locate the low-spin states in $^{195}Tl$. The low-spin $^{195g}Pb$ ($J^{\pi} = 3/2^{-}$) was produced indirectly from $^{195}Bi$ decay. Some preliminary results (for $^{195}Tl$) will be reported at the Vancouver Meeting of the American Physical Society in October 1986. This work is in collaboration with Profs. C. R. Bingham and L. L. Riedinger (Univ. of Tenn.) and E. F. Zganjar.

The eventual goal of the odd-mass Tl studies is again (cf. neutron-deficient Au and Hg isotopes) the establishment of spectroscopic information on shape coexistence in $^{185,187,189}Tl$. The structures $^{A-1}Hg\ (0_1^{+}) \otimes \pi^{+1}$ and $^{A+1}Pb\ (0_1^{+}) \otimes \pi^{-1}$ are already well established in the odd-mass Tl isotopes. However, as in $^{185,187}Au$, the structures $^{A-1}Hg\ (0_2^{+}) \otimes \pi^{+1}$ and $^{A+1}Pb\ (0_2^{+}) \otimes \pi^{-1}$ should also be seen if the "proton-pair" picture (see above) of shape coexistence is correct.

Later this contract year a study of yrast state lifetimes in $^{189,191}Tl$, by the recoil distance technique, is planned at ATLAS. The aim of these experiments is to obtain transition quadrupole moments in the $\pi h_{9/2}$ intruder (shape coexisting) band via B(E2) values. These can be compared with the spectroscopic quadrupole moments deduced from laser atomic hyperfine spectroscopy studies (J. A. Bounds et al., Phys. Rev. Lett. 55, 2269 (1985)), which argue for an exact cancellation between deformation effects and neutron pairing effects to explain the constant energy spacings of the $\pi h_{9/2}$ intruder bands throughout the odd-mass Tl isotopes. This work is in collaboration with Prof. U. Garg (Univ. of Notre Dame), and the in-beam spectroscopy group at Argonne National Laboratory.

### 2.4 Neutron-Deficient Pb Isotopes

A study of the $^{192,194,196,198,200}Bi \rightarrow {}^{192,194,196,198,200}Pb$ decay schemes has been completed, and a paper has been prepared for publication. This work was done at the LISOL facility in collaboration with the nuclear spectroscopy group at IKS, Leuven, Belgium.

Laser atomic hyperfine spectroscopy of neutron-deficient Pb isotopes has been successfully initiated at UNISOR with measurements on $^{196}Pb$. Running time is scheduled for later this year to measure $^{195,194}Pb$ and possibly $^{192}Pb$. The goal of these studies is to eventually reach $^{187,188,189,190}Pb$ where shape coexistence effects are expected to be observable. These may be smooth and weak if the effect is limited to mixing of a deformed excited configuration into the ground state, or it may be sudden and strong if the deformed configuration intrudes to dominate the ground state structure. This work is in collaboration with the UNISOR consortium and constitutes part of the Ph.D. thesis of J. Griffin, ORAU Fellow/School of Chemistry, Ga. Tech.

### 2.5 Other Decay Scheme Studies

A study of the lifetimes of yrast states in $^{184}Pt$ has been completed, and a paper has been prepared for publication. This work was done at ATLAS in collaboration with Notre Dame and the ATLAS in-beam group at Argonne National Laboratory.

A study of the alpha decay of $^{197}At$ to $^{193}Bi$ has been completed, and a paper has been prepared for publication. This work was done at the LISOL facility in collaboration with the nuclear spectroscopy group at IKS, Leuven, Belgium.

## 3.0 Nuclear Systematics and Models

The development of nuclear systematics and models continues to be a major activity on this contract. Five areas have been pursued in the past year: systematics in the neutron-deficient Au isotopes; proton-neutron interacting boson model calculations for the neutron-deficient Pt isotopes; particle-core coupling calculations in the neutron-deficient Au, Hg and Tl isotopes; intruder states and shape coexistence; and a description of collective negative parity states in the rare-earth region in terms of the interacting boson model.

The systematic features of the neutron-deficient Au isotopes have become considerably clearer in the past year. This has been helped greatly by the study of levels in $^{185}$Au. As noted in Section 2.1 above, four distinct structures in $^{185}$Au have been observed: $^{184}$Pt $(0_1^+) \otimes \pi^{+1}$; $^{184}$Pt $(0_2^+) \otimes \pi^{+1}$; $^{186}$Hg $(0_1^+) \otimes \pi^{-1}$; and $^{186}$Hg $(0_2^+) \otimes \pi^{-1}$. The notation here implies, e.g., $^{184}$Pt $(0_1^+) \equiv$ the ground state structure of $^{184}$Pt and associated collective modes; $\pi^{+1} \equiv h_{9/2}$, $f_{7/2}$, $i_{13/2}$. Three of these structures are clearly identifiable in $^{187}$Au. The uncertain one is $^{188}$Hg $(0_2^+) \otimes \pi^{-1}$ -- candidates exist for a strongly coupled band built on this structure ( $\pi^{-1} = s_{1/2}$, $d_{3/2}$), but existing data are inadequate to be sure that all low-lying states have been seen (see the accompanying Renewal Proposal for plans to study this further). These systematics were discussed in invited papers presented at the Dubrovnik Conference in June 1986, and the Anaheim Symposium in September 1986. A paper was submitted for publication in the Proceedings of the Dubrovnik Conference. Some results will also be reported at the Vancouver Meeting of the American Physical Society in October 1986. This work is in collaboration with E. F. Zganjar.

Theoretical studies of the neutron-deficient Au isotopes are being pursued using the "Duval and Barrett" prescription for shape coexistence (P. Duval and B. R. Barrett, Phys. Lett. 100B, 223 (1981)) formulated in terms of the interacting proton-neutron boson model to describe the neighboring doubly-even cores; and the Dönau-Frauendorf prescription for particle-core coupling (F. Dönau and S. Frauendorf, Phys. Lett. 71B, 263 (1977)). This work is being done in collaboration with B. E. Gnade and P. B. Semmes. Closely related to this and an outcome of it is the testing of interacting proton-neutron boson model core descriptions through particle-core coupling (where the unpaired nucleon acts as a probe of the core). A paper has been submitted for publication. This work is in collaboration with B. E. Gnade, P. Semmes and the theory group of B. R. Barnett at the Univ. of Arizona, Tucson.

Shape coexistence and intruder states has continued with a study of particle-hole interaction matrix elements and Coulomb matrix elements (a short paper is in press with Physics Letters); and a complete discussion of the ideas that appeared in Phys. Lett. 155B, 303 (1985) is in preparation.

A study of collective negative parity states (octupole states) in the rare earth region has been completed. (This completes the study of degrees of freedom outside of the s-d model space of the interacting boson model.) Some details were reported at the Dubrovnik Conference and a paper was submitted for publication in the Proceedings. A short paper has also been submitted to Physical Review C. A larger paper is nearing completion.

## 4.0 Personnel

### Senior Staff

Dr. J. L. Wood, Associate Professor, Principal Investigator. Full time 8 months.

### Graduate Students

Mr. Chris Papanicolopulos, Ph.D. thesis work. Half time 6 months.

## 5.0 Summary of Publications and Preprints, Abstracts and Presentations at Conferences, 1985

1. "A New Prescription for Determining Particle-Hole Interactions Near Closed Shells", K. Heyde, J. Jolie, J. Moreau, J. Ryckebusch, M. Waroquier, and J. L. Wood, Phys. Lett. (in press).
2. "An Interacting Boson Model Study of Octupole States in Deformed Nuclei", A. F. Barfield, J. L. Wood, and B. R. Barrett, preprint.
3. "Testing IBM Cores Through Particle-Core Coupling: Negative Parity States in the Odd-mass Tl and Au Isotopes", P. B. Semmes, A. F. Barfield, B. R. Barrett, and J. L. Wood, preprint.
4. "First Identification of a $1/2^+$ Intruder State in the $^{197}$At Isotope", E. Coenen, K. Deneffe, M. Huyse, P. van Duppen, and J. L. Wood, preprint.
5. "The $\beta^+$/EC Decay of $^{192,194,196,198,200}$Bi: Experimental Evidence for Low-Lying $0^+$ States", P. van Duppen, E. Coenen, K. Deneffe, M. Huyse, and J. L. Wood, preprint.
6. "Sudden Change in the Nuclear Charge Distribution of Very Light Gold Isotopes", K. Wallmeroth, G. Bollen, A. Dohn, P. Egelhof, J. Gruner, F. Lindenlauf, U. Kronert, J. Campos, A. Rodriguez Yunta, M. J. G. Borge, J. L. Wood, R. B. Moore, A. Venugopalan, and H.-J. Kluge, preprint.
7. "Lifetime Measurements in $^{184}$Pt: Evidence for Shape Coexistence", U. Garg, A. Chandhury, M. W. Drigert, E. G. Funk, J. W. Mihelich, D. C. Radford, H. Helppi, R. Holzmann, R. V. F. Janssens, T. L. Khoo, A. M. Van den Berg, and J. L. Wood, preprint.
8. "Magnetic Moment Determination of $^{185,186}$Au and $^{185}$Ir With On-Line Nuclear Orientation", E. Van Walle, D. Vandeplassche, J. Wouters, N. Severijns, L. Vanneste, and J. L. Wood, preprint.
9. "A Study of Octupole Bands Within the Interacting Boson Model",

A. F. Barfield, B. R. Barnett, and J. L. Wood, to be published in Proc. of the Int. Conf. on Nuclear Structure, Reactions, and Symmetries, June 5-14, 1986, Dubrovnik, Yugoslavia.

10. "Shape Coexistence in the Z = 78-82 Region", E. F. Zganjar, J. L. Wood, C. Papanicolopulos, and M. Kortelahti, to be published, ibid.

11. "A Study of Octupole Bands Within the Interacting Boson Model", A. F. Barfield, B. R. Barrett, and J. L. Wood, Contribution to the Int. Conf. on Nuclear Structure, Reactions, and Symmetries, June 5-14, 1986, Dubrovnik, Yugoslavia [abstract].

12. "Shape Coexistence in the Z = 78-82 Region", E. F. Zganjar and J. L. Wood, Invited Paper, ibid. [abstract].

13. "Systematic Studies in the Z = 82 Region: The Structure of Neutron-Deficient Tl, Hg, Au, and Pt Isotopes", E. F. Zganjar and J. L. Wood, Invited Talk given at the Symposium on Nuclear Spectroscopic Quantities - Their Determination and Use, 192nd National Meeting of the American Chemical Society, Sept. 7-12, 1986, Anaheim, California [abstract].

14. "Roundtable Discussion of Nuclear Spectroscopic Quantities - Their Determination and Use", J. L. Wood, ibid. [abstract].

15. "Coexisting Collective Structure in the Neutron-Deficient Au Isotopes", J. L. Wood, C. D. Papanicolopulos, E. F. Zganjar and M. Kortelahti, Contribution to the Vancouver Meeting of the American Physical Society, Oct. 9-11, 1986, Vancouver, Canada [abstract].

16. "Decay of the Low-Spin Isomer of $^{195}$Pb", C. R. Bingham, H. V. Carmichael, V. Janzen, L. L. Riedinger, W. Schmitz, R. A. Braga, R. W. Fink, J. L. Wood, M. Kortelahti, E. F. Zganjar, C. Girit, H. K. Carter, and R. L. Melkodaj, ibid. [abstract].

17. "Decay of Mass-Separated $^{189}$Tl (1.4 min) to $^{189}$Hg", B. E. Gnade,

S. Slaughter, E. F. Zganjar and J. L. Wood, ibid. [abstract].

18. "Band Structures in $^{189}$Au from $^{189m,g}$Hg Decay", M. Kortelahti, E. F. Zganjar, J. L. Wood, R. A. Braga, R. W. Fink, H. K. Carter, and R. L. Melkodaj, Bull. Am. Phys. Soc. 31, 874, JI 9(1986) [abstract].

19. "On-Line RIMS of Very Neutron-Deficient Gold Isotopes", G. Bollen, M. G. Borge, J. Campos, A. Dohn, P. Egelhof, J. Gruner, J. J. Kluge, U. Kronert, F. Lindenlauf, R. B. Moore, A. Rodriguez, A. Venugapalan, J. L. Wood, K. Wallmeroth and the ISOLDE Collaboration, Contribution to the Symposium on Resonant Ionization Mass Spectrometry, Swansea, England, 1986 [abstract].

20. "Nuclear Charge Radii of Neutron-Deficient Short-Lived Gold Isotopes", K. Wallmeroth, G. Bollen, M. J. G. Borge, J. Campos, A. Dohn, P. Egelhof, J. Gruner, H. J. Kluge, U. Kronert, R. B. Moore, A. Rodriguez, A. Venugopalan, J. L. Wood, and the ISOLDE Collaboration, Contribution to the International Conference on Nuclear Physics, Aug. 25-30, 1986, Harrogate, England [abstract].

21. "Resonant Ionization Mass Spectrometry (RIMS) of Short-Lived Gold Isotopes", K. Wallmeroth, G. Bollen, M. J. G. Borge, J. Campos, A. Dohn, P. Egelhof, J. Gruner, H. J. Kluge, F. Lindenlauf, U. Kronert, R. B. Moore, A. Rodriguez, A. Venugopalan, J. L. Wood and the ISOLDE Collaboration, Contribution to ICAP, Tokyo, Japan, 1986 [abstract].

22. "Nuclear Shape Transition in Neutron-Deficient Gold Isotopes", K. Wallmeroth, G. Bollen, M. J. G. Borge, J. Campos, A. Dohn, P. Egelhof, J. Gruner, H. J. Kluge, U. Kronert, R. B. Moore, A. Rodriguez, A. Venugopalan, J. L. Wood, and the ISOLDE Collaboration, Contribution to the Int. Conf. on Hyperfine Interactions, India, 1986 [abstract].

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# NUCLEAR STRUCTURE FROM RADIOACTIVE DECAY

Final Technical Report

February 1, 1980 - January 31, 1987

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May 1987

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The entirety of the work performed in the period February 1,1980 - January 31, 1987 is described in the following annual reports, all with the title: "Nuclear Structure from Radioactive Decay"--

| Report date | Report number |
|---|---|
| October 31, 1980 | DOE/ER/10599 - 2 |
| September 30, 1981 | -10 |
| October 31, 1982 | -17 |
| September 30, 1983 | -21 |
| September 30, 1984 | -34 |
| September 30, 1985 | -46 |
| August 31, 1986 | -66 |

(The work is being pursued further under the new award: Grant No. DE - FG05 - 87ER40330.)